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Multi-objective optimization and comparison framework for the design of Distributed Energy Systems

M. Karmellos*, G. Mavrotas

Laboratory of Industrial and Energy Economics, School of Chemical Engineering, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece

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ABSTRACT

Energy supply in an economic and environmentally friendly configuration is a major challenge for urban energy systems. This paper presents two multi-objective models for the design of Distributed Energy Systems (DES) for satisfying local needs in heating, cooling and electricity. DES can be used to promote energy efficiency and reduce carbon emissions which is crucial to tackle climate change. A multi-objective MILP framework is presented, comparing two main methodologies of designing DES using Total Annual Cost (TAC) and carbon emissions as objective functions. The first one, namely "Method A", which performs a simultaneous sizing and the second one, namely "Method B", in which technologies and their respective capacity are predefined. Furthermore, three scenarios regarding the available technologies are developed to assess DES for both methods and a case study is carried out. Results show that in both methods Scenario 3 (a DES coupled with district heating network, microgrid and storage technologies) has the best performance. In terms of comparison between the two methods, "Method A" provides better solutions in terms of cost and emissions as it has more degrees of freedom. Structure, design and operational results are presented and discussed analytically, as well as the possibility of comparing the two methods for a more detailed design.

1. Introduction

The reduction of greenhouse gases emissions, mainly of carbon dioxide, has been a clear policy target for many countries in the last decades. It is well known that greenhouse effect affects global temperature, which leads to climate change. In 1992 the Kyoto agreement was signed regarding carbon emissions reduction. More recently, in 2016 the Paris agreement for climate change was signed reflecting the will of international community to tackle climate change.

A possible solution to the problem of climate change could be the exploitation of renewable energy sources (RES), which are in abundance and provide a clean alternative to conventional fuels. However, RES have the disadvantage of being intermittent. In order to deal with this issue, distributed energy systems (DES) could be designed and used to combine RES with other conventional technologies (e.g. cogeneration) in order to satisfy electricity, heating and cooling energy demand of consumers. In literature, it has been shown that DES systems can be operational and offer multiple benefits, such as reduced costs, reduced carbon emissions, increased energy autonomy, hence making them an attractive alternative for future urban and semi-urban energy systems.

DES offer several advantages compared to traditional energy systems. Firstly, DES are installed closer to the consumer which means they can satisfy the energy demand with minimal transmission or distribution losses. Secondly, some DES technologies can be used to exploit waste energy in order to increase the overall system efficiency, therefore minimizing primary energy consumption leading to reduction of carbon dioxide emissions. Therefore, DES can be furtherly exploited to tackle climate change. Moreover, DES allow the exploitation of local RES such as solar photovoltaics, wind turbines and solar thermal collectors which offer several economic and environmental benefits. Regarding conventional technologies, a number of technologies can be used for the design of DES, such as combined heat and power (CHP) systems, heat pumps, absorption chillers, boilers, and storage units (thermal or electricity storage). However, although DES offer many advantages, designing such systems is not a trivial task. It is a long-term energy planning complex problem with many aspects to be taken into consideration, such as the economic cost, the location of the buildings, the available technologies (either conventional or RES), energy loads, and environmental cost (in terms of CO_2 emissions). There are different methodologies developed for the design of a DES, each of them having its own advantages and disadvantages.

* Corresponding author.
E-mail address: mkarmellos@chemeng.ntua.gr (M. Karmellos).

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Nomenclature

Sets

sco	set of CHP units
shp	set of heat pumps
sch	set of absorption chillers
sb	set of boilers
swt	set of wind turbines
i	the set of buildings of the DES
d	number of the typical days a year is divided
p	number of the periods a typical day d is subdivided

Parameters regarding the buildings, the time horizon, and the climate

$l_{i,j}$	the matrix representing the distance between building i and building j [m]
n_d	the number of days a typical d day represents in year
δ_p	the duration of time periods p in hours
α_i	the available surface in building i for the installation of solar photovoltaics and/or collectors [m^2]
$d^{el}_{i,d,p}$, $d^{h}_{i,d,p}$, $d^{c}_{i,d,p}$	are respectively the electric, heating and cooling energy loads of building *i* at period *p* of day *d* [kW]
$r^{DHW}_{i,d,p}$	the ratio of demand for DHW over the total heating load of building *i* at period *p* of day *d*
$i^{sol}_{d,p}$	the solar irradiance at period *p* of day *d* [kW/m^2]

Parameters regarding technologies (size, cost, efficiency) and DHN

a_n	capital recovery factor for technologies
n	lifetime of technologies [years]
s^{wt}_{swt}	size of wind turbine technologies in set*swt*
$w_{swt,d,p}$	electricity generation of a wind turbine of *swt* set at period p of day d [kW]
ub^{CHP}, lb^{CHP}	upper and lower bound for the size of CHP [kW]
ub^{HP}, lb^{HP}	upper and lower bound for the size of heat pumps [kW]
ub^{CHIL}, lb^{CHIL}	upper and lower bound for the size of absorption chillers [kW]
ub^{B}, lb^{B}	upper and lower bound for the size of boilers [kW]
ub^{PV}	upper bound for the size of photovoltaics [kW]
ub^{TS}	the maximum thermal energy that can be stored in heat storage technology [kWh]
ub^{ES}	the maximum electrical energy that can be stored in heat storage technology [kWh]
c^{wt}_{swt}	the capital cost of wind turbines of *swt*set [€/kW]
c^{chp}_{fix}	fixed capital cost of CHP [€]
c^{chp}_{lin}	linear capital cost of CHP [€/kW]
c^{HP}	capital cost of heat pumps [€/kW]
c^{CHIL}	capital cost of absorption chillers [€/kW]
c^{B}	capital cost of boilers [€/kW_{th}]
c^{PV}	capital cost of solar photovoltaics [€/kW]
c^{ST}	capital cost of solar thermal collectors [€/m^2]
c^{ES}	capital cost of electricity storage technology [€/kWh]
c^{TS}	capital cost of thermal storage technology [€/kWh]
c^{MG}	capital cost of microgrid controller [€]
c^{p}	capital cost of pipes [€/m]
μ^{WT}_{swt}	maintenance cost of wind turbines of *swt*set [€/kWh]
μ^{CHP}	maintenance cost of CHP technologies [€/kWh]
μ^{HP}	maintenance cost of heat pumps [€/kWh]
μ^{CHIL}	maintenance cost of absorption chillers [€/kWh]
μ^{B}	maintenance cost of boilers [€/kW_{th}]
μ^{pv}	maintenance cost of solar photovoltaics [€/kW]
μ^{st}	maintenance cost of solar thermal collectors [€/m^2]
μ^{TS}	maintenance cost of thermal storage technology [€/kWh]
k^{CHP}	part load factor for the operation of CHP
η^{CHP_el}	the electrical efficiency of CHP [%]
η^{CHP_th}	the electrical efficiency of CHP [%]
η^{B}	efficiency of boiler [%]
η^{CH}	efficiency of absorption chiller [%]
COP^{hp}_{th}, COP^{hp}_{c}	coefficient of performance of heat pumps for heating and cooling
η^{pv}	efficiency of solar pv [%]
η^{st}	efficiency of solar thermal collectors [%]
$\eta^{es,in}$, $\eta^{es,out}$	charging and discharging efficiency of electric storage [%]
pv^{cof}	power density of solar pv [kW/m^2]
β^{p}	heat losses through pipes [1/m]
d^{WT}_{i}	a parameter indicating the availability of installing a wind turbine at building *i*
etl	electricity transmission losses [%]

Other parameters

r	discount rate [%]
f^{grid}	carbon emission factor of the national grid [kg CO_2/kWh]
f^{ng}	carbon emission factor of natural gas [kg CO_2/kWh]
c^{ng}	cost of natural gas [€/kWh]
$c^{el\_buy}_{d,p}$	cost of buying electricity at period *p* of day *d* [€/kWh]
$c^{CHP\_sell}_{d,p}$	cost of selling electricity from CHP at period *p* of day *d* [€/kWh]
$c^{PV\_sell}_{d,p}$	cost of selling electricity from PV at period *p* of day *d* [€/kWh]
$c^{WT\_sell}_{d,p}$	cost of selling electricity from wind turbines at period *p* of day *d* [€/kWh]

Positive decision variables

C^{T}	total annual cost (€)
C^{C}	capital cost (€)
C^{O}	operational cost (€)
C^{M}	maintenance cost (€)
$CARBON^{T}$	total carbon emissions (kg/year)
$CARBON^{F}$	fuel-based carbon emissions (kg/year)
$CARBON^{E}$	electricity-based carbon emissions (kg/year)
S^{CHP}_{i}	size of CHP unit at building *i* [kW]
S^{HP}_{i}	size of heat pump unit at building *i* [kW]
$S^{HP\_h\_aux}_{i}$	an auxiliary variable for the linearization of heat pumps operation
S^{CHIL}_{i}	size of absorption chiller unit at building *i* [kW]
S^{B}_{i}	size of boiler unit at building *i* [kW]
S^{PV}_{i}	size of photovoltaics at building *i* [kW]
A^{PV}_{i}	area of photovoltaics at building *i* [m^2]
A^{ST}_{i}	size of solar thermal collectors at building *i* [m^2]
Q^{ES}_{i}	rated electricity storage at building *i* [kWh]
Q^{TS}_{i}	rated thermal storage at building *i* [kWh]
$Z^{CHP}_{i,d,p}$	primary energy consumption of CHP at building *i* at period *p* of day *d* [kW]
$Z^{B}_{i,d,p}$	primary energy consumption of boilers at building *i* at period *p* of day *d* [kW]
$E^{el\_grid}_{i,d,p}$	electricity bought from grid at building *i* at period *p* of day *d* [kW]
$E^{CHP}_{i,d,p}$	total electricity generation of CHP at building *i* at period *p* of day *d* [kW]
$E^{CHP\_build}_{i,d,p}$	electricity generation of CHP for use at building *i* at period *p* of day *d* [kW]
$E^{CHP\_sell}_{i,d,p}$	electricity generation of CHP sold to grid from building *i* at period *p* of day *d* [kW]
$E^{CHP\_mg}_{i,d,p}$	electricity generation of CHP sent to microgrid from building *i* at period *p* of day *d* [kW]
$Q^{CHP}_{i,d,p}$	total heating energy generation of CHP at building *i* at period *p* of day *d* [kW]
$Q^{CHP\_build}_{i,d,p}$	heating energy generation of CHP used at building *i* at period *p* of day *d* [kW]

$Q_{i,d,p}^{CHP\_net}$ heating energy generation of CHP sent to DHN from building i at period p of day d [kW]
$Q_{i,d,p}^{HP\_h}$ total heating energy generation of heat pump unit at building i at period p of day d [kW]
$Q_{i,d,p}^{HP\_h\_build}$ heating energy generation of heat pump used at at building i at period p of day d [kW]
$Q_{i,d,p}^{HP\_h\_net}$ heating energy generation of heat pump sent to DHN from building i at period p of day d [kW]
$Q_{i,d,p}^{HP\_c}$ cooling energy generation of heat pump unit at building i at period p of day d [kW]
$E_{i,d,p}^{HP}$ electricity used by heat pump unit at building i at period p of day d [kW]
$Q_{i,d,p}^{CH\_c}$ cooling energy generation of absorption chiller at building i at period p of day d [kW]
$Q_{i,d,p}^{CH\_abs}$ thermal energy absorbed from absorption chiller at building i at period p of day d [kW]
$Q_{i,d,p}^{B}$ total heating energy generation of boiler at building i at period p of day d [kW]
$Q_{i,d,p}^{B\_build}$ heating energy generation of boiler used at building i at period p of day d [kW]
$Q_{i,d,p}^{B\_net}$ heating energy generation of boiler sent to DHN from building i at period p of day d [kW]
$E_{i,d,p}^{PV}$ total electricity generation from photovoltaics at building i at period p of day d [kW]
$E_{i,d,p}^{PV\_build}$ electricity generation from photovoltaics used at building i at period p of day d [kW]
$E_{i,d,p}^{PV\_sell}$ electricity generation from photovoltaics sold to grid from building i at period p of day d [kW]
$E_{i,d,p}^{PV\_mg}$ electricity generation from photovoltaics sent to microgrid from building i at period p of day d [kW]
$E_{i,d,p}^{WT}$ total electricity generation from wind turbine at building i at period p of day d [kW]
$E_{i,d,p}^{WT\_build}$ electricity generation from wind turbine used at building i at period p of day d [kW]
$E_{i,d,p}^{WT\_sell}$ electricity generation from wind turbine sold to grid from building i at period p of day d [kW]
$E_{i,d,p}^{WT\_mg}$ electricity generation from wind turbine sent to microgrid from building i at period p of day d [kW]
$E_{i,d,p}^{MG}$ electricity received from microgrid at building i at period p of day d [kW]
$E_{i,d,p}^{sell}$ total electricity sold to grid from building i at period p of day d [kW]
Q_i^{ES} rated electricity storage at building i [kWh]
Q_i^{TS} rated thermal storage at building i [kWh]
$E_{i,d,p}^{ES}$ electricity stored at building i at period p of day d [kWh]
$E_{i,d,p}^{TS}$ thermal energy stored at building i at period p of day d [kWh]
$E_{i,d,p}^{ES\_in}$, $E_{i,d,p}^{ES\_out}$ electricity charged and discharged from storage at building i at period p of day d [kW]
$Q_{i,d,p}^{TS\_in}$, $Q_{i,d,p}^{TS\_out}$ thermal energy charged and discharged to storage at building i at period p of day d [kW]

Binary variables

Y_i^{CHP} if CHP is installed at building i
Y_i^{WT} if wind turbine is installed at building i
$Y_{i,j}^{HN\_SUP}$, $Y_{i,j}^{HN\_RET}$ if a supply (and a return pipe) is installed between building i and building j
Y^{MG} if microgrid is installed
Y_i^{HP} if a heat pump is installed at building i
Y_i^{CHIL} if an absorption chiller is installed at building i
X_i^{CHP} if CHP operates at building i at period p of day d
$X_{i,d}^{HP\_h}$ if heat pump at building i operates in heating mode at day d
$X_{i,d,p}^{HP\_h}$ if heat pump at building i operates in heating mode at period p of day d
$X_{i,d}^{HP\_c}$ if heat pump at building i operates in cooling mode at day d
$X_{i,d,p}^{HP\_c}$ if heat pump at building i operates in cooling mode at period p of day d
$X_{i,d,p}^{el\_sell}$ if electricity is sold to grid from building i at period p of day d

1.1. Literature review

In literature several approaches were made for the design of a DES, most of them using a Mixed-Integer Linear Programming (MILP) model with the single objective of reducing total annual costs (TAC). DES could be designed either for a single building or for a set of buildings (e.g. a neighbourhood or a district). An energy systems engineering framework has been developed by Liu et al. in [1] for the optimal design of energy systems in a commercial building using a multi-period multi-objective MIP model with economic and environmental objective functions. Buoro et al. in [2] present a MILP model for the optimization of energy supply systems for two buildings with total costs as the objective function. The same authors in [3] developed a multicriteria optimization model of a DES for an industrial area using the concept of a superstructure. A MILP model was presented with annual cost and carbon emissions as objective functions and solved with the weighted sum method. Kopanos et al. in [4] present a mathematical programming framework for operational strategy of micro CHP units, by minimizing total costs. Uncertainty in specific parameters can also be addressed using a combination of mathematical programming and Monte Carlo simulation providing an energy planning framework to be used in buildings by minimizing the annualized cost [5]. In [6] a MILP superstructure model is presented for the optimal design of DES, satisfying the heat and power demand at local residential level. The objective is the optimal selection of the system components and the optimal design of the district heating network (DHN) by using the total annual costs as the objective function. In [7] the same authors provide a framework for the integrated planning and evaluation of DES, taking into account energy demand, local climate data, utility tariffs, technical characteristics of technologies and geographical aspects used in a case study for a neighbourhood. Weber & Shah in [8] present a tool that identifies the optimal configuration and sizes of technologies by minimizing total annual costs. It is applied in an eco-town in the United Kingdom using both conventional technologies and renewables, either installed centrally or decentralized. In [9] a MILP model is presented for the optimal selection and sizing of technologies, unit location and distribution network in order to satisfy heating and electricity demand, using as objective function the minimization of total annual costs. In [10] a structural and operational optimization by Haikarainen et al. is presented, more specifically for the design of a district heating system in an urban area using MILP. In [11] Yang et al. developed a MILP model for the simultaneous optimization of locations, configuration and structure of energy distributed networks with total annual cost as the objective function. A detailed MILP model for the design of DES is presented by Bracco et al. in [12]. The model provides a superstructure approach for the selection of different technologies that satisfy heating, cooling and electricity demand for an urban district. Although buildings can be interconnected by means of a DHN to exchange heating, cooling is provided locally whilst electricity is transferred by a microgrid through a single connection point with the national grid. Also, the authors performed a computational analysis to examine the impact of the dimensions on a MILP model.

In [13] Ren et al. developed a multi-objective optimization model that analyses the optimal operating strategy of a DES, with minimization of energy costs and carbon emissions as the two objective functions. Multi-objective optimization for the design and operation of DES

was also studied by Fazlollahi et al. in [14]. The authors developed a model that considers process and energy integration. They performed decomposition optimization where in the master optimization phase the objective functions where the maximization of the system efficiency, the minimization of CO_2 emissions and the minimization of total annual costs. In the slave optimization phase, they developed a MILP model for the energy integration with the objective of minimizing total operation and emissions costs.

Di Somma et al. in [15] developed a multi-objective optimization model of a DES for the calculation of optimal operation strategies in order to minimize energy costs and environmental impacts using the weighted sum method. The same authors in [16] provide an operation optimization of a DES using multi-objective optimization solved with the weighted sum method where in this case the one objective function is the total primary exergy input and the other being the total energy costs. The weighted sum method was also used by Cedillos Alvarado et al. in [17] to develop a technology selection and operation optimization model for DES with three objective functions, namely minimizing total annual costs, minimizing annual emissions and as third function minimizing the weighted sum of the total cost and total emissions. Their method can be used to perform several optimizations to evaluate the economic and environmental trade-offs.

Falke et al. [18] present a multi-objective optimization model of the investment planning and operation management of distributed heat and electricity supply systems, by taking into account several energy efficiency measures and supply options. The objective functions are the minimization of the annual costs of energy supply and the carbon emissions. To reduce complexity, they decompose the optimization into three sub-models and applied the model into a town in Germany.

Morvaj et al. in [19] presented a multi-objective MILP model for the optimal design and operation of DES and for the design of heating network layouts. Their model calculates the optimal configuration of technologies for the district system and the optimal sizes, having as objective functions the minimization of total costs and carbon emissions and it was solved using the ε-constraint method.

In [20] Sameti and Haghighat proposed a two level multi-objective optimization for designing a trigeneration system to cover the heating, cooling and hot water loads using total annual cost and carbon emissions as objective functions. The method was tested in a virtual district with eight buildings using also some backup technologies and the results show a significant reduction of costs and emissions.

More recently, Juing et al. in [21] proposed a framework for optimizing distributed energy systems, using multi-objective optimization and multi-criteria evaluation simultaneously by Analytic Hierarchy Process and Gray Relation Analysis. Their model was applied in a solar-assisted solid oxide fuel cell distributed energy system, which was tested in a hospital and a hotel in three different climate zones.

1.2. Scope

Despite several optimization models developed for the design of DES, either single or multi-objective, to our consideration there is an aspect that needs to be further examined. In literature there are two main approaches for the design of DES, one being the method which simultaneously optimizes the size of the technologies (“Method A”) or the second one which offers the selection of the system components amongst a set of available technologies with predefined sizes (“Method B”). Hence, we believe that there is a need to compare those two approaches in order to assess their advantages and disadvantages.

Therefore, the purpose of this paper is twofold:

(a) Provide two multi-objective models for the design of a DES with two objective functions, namely, the TAC (which includes capital, operational and maintenance costs), and the total annual CO_2 emissions. The two models are based on two different design methods, namely “Method A” and “Method B” respectively, and are formulated as generic mixed-integer linear programming (MILP) models for the design of DES, providing the following outputs:
- The technologies and their respective sizes that will be installed at each building;
- The layout of the district heating network (DHN)
- The operational profile of the installed technologies
- The electricity exchange between the national grid and microgrid (if one is installed);

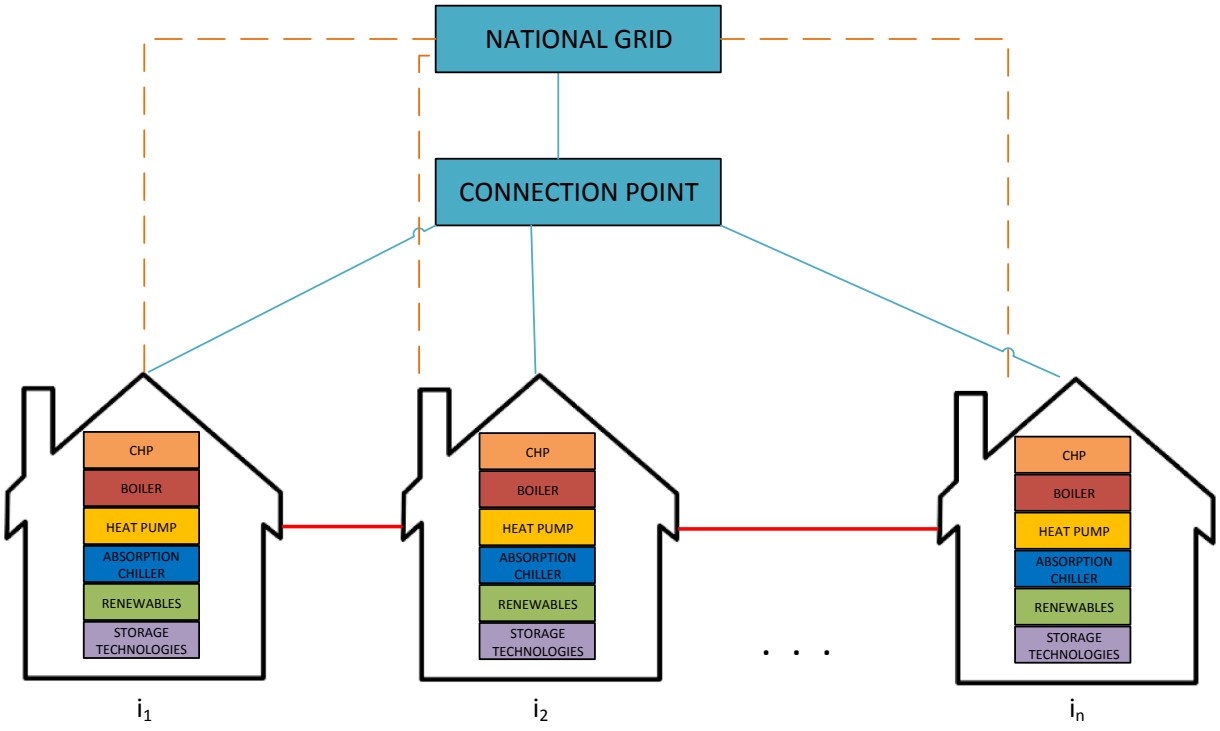


Fig. 1. A sketch of the DES.

(b) Provide a comparison between the two methodologies, as well as a comparison among three different scenarios of available technologies.

The paper is organized as follows: Section 2 describes the methodologies for the design of DES, followed by Section 3 where a case study is developed. In Section 4 the results of the case study are presented and discussed. Finally, Section 5 concludes the paper.

2. Methodology

This paper presents a multi-objective MILP mathematical programming model using two methods for the design of a DES. The considered DES comprises of different technologies which could be installed at each building and satisfy end-users energy demands in heating (including domestic hot water (DHW)), cooling or electricity. The available energy technologies are both conventional and renewables, namely: CHP units, boilers, heat pumps, absorption chillers, solar photovoltaics, solar collectors, wind turbines, and electric and thermal storage technologies. An illustration of the proposed concept of the DES is presented in Fig. 1. This model is based on the principle that in terms of thermal energy buildings are allowed to exchange only heating, hence an optimal DHN configuration is also available as an output. That means the optimal interconnections and optimal heat transfer periods will be calculated. Buildings form a decentralized network where heat could either be consumed or produced, and it is assumed that any building could be connected with any other one. In terms of electricity, buildings are allowed to exchange electricity with the grid (buying or selling) or there is the availability to form a microgrid and exchange electricity [7,12]. Cooling demand is satisfied locally at each building with no cooling network designed.

The time horizon for the calculations is set to be a typical year, which can be divided into representative days. Furthermore, the time horizon is further subdivided into typical periods of each day. The model is generic, and the decision maker could set these parameters according to his preferences.

Both methods are based on a multi-objective MILP framework solved using the ε – constraint method, which is suitable due its ability to generate non-extreme solutions and providing an efficient trade-off between conflicting objectives [22]. In ε – constraint method a multi-objective problem is reformulated into a single objective one by converting the other objective(s) function(s) into inequality constraints [23].

2.1. "Method A" for the design of a DES

In "Method A" the proposed model can determine the optimal configuration of the DES and the respective capacities of the technologies. The decision maker can select the available technologies and provide the respective lower and upper bounds for their size in order to determine the optimal size and operation simultaneously.

2.1.1. Objective functions

As aforementioned, the two objective functions are the minimization of TAC and total carbon emissions. TAC comprises of the total capital cost for all technologies used, the total operational and maintenance cost as shown in Eq. (1), and total carbon emissions comprise of the emissions generated from fuel-based and from electricity-based technologies respectively, as shown in Eq. (2).

$$f_1(x):\ C^T = C^C + C^O + C^M \tag{1}$$

$$f_2(x):\ CARBON^T = CARBON^F + CARBON^E \tag{2}$$

Regarding the application of ε – constraint method, the TAC is the primary objective function, and carbon emissions the secondary one which subsequently is applied as a constraint.

For the calculation of the first objective function, the capital cost of the DES consists of the annualized capital cost for each technology, the cost of laying pipes for the interconnections in DHN design and the cost for microgrid, as described in Eq. (3).

$$C^C = \sum_i \begin{bmatrix} a_n^{CHP}\cdot(c_{fix}^{CHP}\cdot Y_i^{CHP} + c_{lin}^{CHP}\cdot S_i^{CHP}) + a_n^{HP}\cdot c^{HP}\cdot S_i^{HP} + a_n^{CHIL}\cdot c^{CHIL}\cdot S_i^{CHIL} \\ + a_n^{PV}\cdot c^{PV}\cdot S_i^{PV} + a_n^{ST}\cdot c^{ST}\cdot A_i^{ST} + a_n^{B}\cdot c^{B}\cdot S_i^{B} + a_n^{ES}\cdot c^{ES}\cdot Q_i^{ES} \\ + a_n^{TS}\cdot c^{TS}\cdot Q_i^{TS} + a_n^{WT}\cdot(\sum_{swt} c_{swt}^{WT}\cdot S^{WT}\cdot Y_{i,swt}^{WT}) + a_n^{MG}\cdot c^{MG}\cdot Y^{MG} \\ + a_n^{P}\cdot c^{p}\cdot l_{i,j}\cdot(Y_{i,j}^{HN\_SUP} + Y_{i,j}^{HN\_RET}) \end{bmatrix} \tag{3}$$

The capital recovery factor a^{tech} is calculated by Eq. (4) and it takes into account the lifespan of the equipment into consideration n and the discount rate r:

$$a_n = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{4}$$

The operational cost is given by Eq. (5) and consists of the cost of natural gas for the fuel-based technologies (CHP and boilers) and the cost of buying and selling electricity to the grid:

$$C^O = \sum_i \sum_d \sum_p \delta_p\cdot n_d \begin{bmatrix} c^{ng}(Z_{i,d,p}^{CHP} + Z_{i,d,p}^{B}) + c_{d,p}^{el\_buy}\cdot E_{i,d,p}^{el\_grid} \\ - (c^{PV\_sell}\cdot E_{i,d,p}^{PV\_sell} + c^{WT\_sell}\cdot E_{i,d,p}^{WT\_sell} + c^{CHP\_sell}\cdot E_{i,d,p}^{CHP\_sell}) \end{bmatrix} \tag{5}$$

Finally, the maintenance cost of the technologies configuring the DES is calculated by Eq. (6) as follows:

$$C^M = \sum_i \sum_d \sum_p \begin{bmatrix} \delta_p\cdot N_d\cdot\mu^{CHP}\cdot E_{i,d,p}^{CHP} + \mu^{HP}\cdot E_{i,d,p}^{HP} + \mu^{CHIL}\cdot Q_{i,d,p}^{CHIL} + \mu^{B}\cdot Q_{i,d,p}^{B} \\ + (\sum_{swt}\mu_{swt}^{WT}\cdot E_{i,d,p}^{WT}\cdot Y_{i,swt}^{WT}) + \mu^{TS}\cdot E_{i,d,p}^{TS} + \mu^{PV}\cdot S_{i,d,p}^{PV} + \mu^{ST}\cdot S_{i,d,p}^{ST} \end{bmatrix} \tag{6}$$

For the calculation of the second objective function, the carbon emissions are calculated by Eqs. (7) and (8) respectively:

$$CARBON^F = \sum_i \sum_d \sum_p [\delta_p\cdot n_d\cdot(Z_{i,d,p}^{CHP} + Z_{i,d,p}^{B})\cdot f^{ng}] \tag{7}$$

$$CARBON^E = \sum_i \sum_d \sum_p \delta_p\cdot n_d\cdot E_{i,d,p}^{el\_grid}\cdot f^{grid} \tag{8}$$

2.1.2. Constraints

The constraints of the problem are further divided into different categories, such as system layout, operational constraints for each technology and energy balances for electricity, heating and cooling.

2.1.2.1. System layout. Regarding the installation of technologies there are limits in the number of technologies that can be installed at each building. Eq. (9) states that at most one heat pump or absorption chiller unit can be installed at each building:

$$Y_i^{HP} + Y_i^{CHIL} \leqslant 1 \quad \forall\, i \tag{9}$$

Also, for the solar technologies, the area used by photovoltaics or solar collectors cannot exceed the available roof area in each building as described in Eq. (10).

$$A_i^{PV} + A_i^{ST} \leqslant a_i \quad \forall\, i \tag{10}$$

2.1.2.2. CHP installation and operation. A first set of constraints regarding CHP ensures that if a unit is installed, its optimal capacity needs to be between a lower and an upper bound. Also, the power output of the unit will be lower or equal to its size:

$$S_i^{CHP} \geqslant Y_i^{CHP}\cdot lb^{CHP} \quad \forall\, i \tag{11}$$

$$S_i^{CHP} \leqslant Y_i^{CHP}\cdot ub^{CHP} \quad \forall\, i \tag{12}$$

$$E_{i,d,p}^{CHP} \leqslant S_i^{CHP} \quad \forall\, i, d, p \tag{13}$$

Moreover, due to technical limitations if a CHP unit is installed it needs to operate above a minimum part load. The efficiency of the CHP is considered to be roughly constant above this point, which consists a valid assumption in order to keep the model linear [19]:

$$E_{i,d,p}^{CHP} \leqslant C \cdot X_{i,d,p}^{CHP} \quad \forall\, i, d, p \tag{14}$$

$$S_i^{CHP} \cdot k^{CHP} \leqslant E_{i,d,p}^{CHP} + C \cdot (1 - X_{i,d,p}^{CHP}) \quad \forall\, i, d, p \tag{15}$$

where C is a sufficiently large number.

Regarding the electricity output of the CHP, it is assumed that if a CHP unit is installed and operational the generated electricity would be available for local consumption (building), exported to the grid (sale) or exchanged through the microgrid (if it exists):

$$E_{i,d,p}^{CHP} = E_{i,d,p}^{CHP\_build} + E_{i,d,p}^{CHP\_sell} + E_{i,d,p}^{CHP\_mg} \quad \forall\, i, d, p \tag{16}$$

Also, a CHP unit generates heat when is operational as described by Eq. (17). The generated heat could be used to satisfy building's heat demand or exported to the DHN:

$$Q_{i,d,p}^{CHP} = E_{i,d,p}^{CHP} \cdot \frac{n^{CHP\_th}}{n^{CHP\_el}} \quad \forall\, i, d, p \tag{17}$$

$$Q_{i,d,p}^{CHP} = Q_{i,d,p}^{CHP\_build} + Q_{i,d,p}^{CHP\_net} \quad \forall\, i, d, p \tag{18}$$

Finally, the fuel consumption of CHP is calculated by Eq. (19):

$$Z_{i,d,p}^{CHP} = \frac{E_{i,d,p}^{CHP}}{n^{CHP\_el}} \quad \forall\, i, d, p \tag{19}$$

2.1.2.3. Heat pumps installation and operation. Heat pumps could be used to produce either heating or cooling. There are many models of heat pumps available using different primary energy sources, e.g. air/air, air/water, water/water etc. In this methodology heat pumps are reversible air/water heat pumps. The reason for this selection is that air/water heat pumps can generate water which could be later sent to the network, or stored, in contrast with the air/air heat pumps that could be used to satisfy only local needs. A first, a set of constraints is used to ensure that a heat pump would operate only in heating or cooling mode at a specific representative day:

$$X_{i,d}^{HP\_h} + X_{i,d}^{HP\_c} \leqslant Y_i^{HP} \quad \forall\, i, d \tag{20}$$

$$\sum_p X_{i,d,p}^{HP\_h} \leqslant |p| \cdot X_{i,d}^{HP\_h} \quad \forall\, i, d \tag{21}$$

$$\sum_p X_{i,d,p}^{HP\_c} \leqslant |p| \cdot X_{i,d}^{HP\_c} \quad \forall\, i, d \tag{22}$$

When a heat pump operates, either in heating or cooling mode, the generated energy needs to be lower than its capacity. However, due to its dual mode of operation this would result in non-linear equations and in order to avoid this and keep the model linear, auxiliary variables are introduced based on the concept of linearizing the product of a continuous variable (size) and a binary variable (mode of operation). Therefore, for heating mode the set of Eqs. (23)–(26) is used. A similar set of equations exists for the cooling mode linearization.

$$S_{i,d,p}^{HP\_h\_aux} \leqslant ub^{HP} \cdot X_{i,d,p}^{HP\_h} \quad \forall\, i, d, p \tag{23}$$

$$S_{i,d,p}^{HP\_h\_aux} \leqslant S_{i,d,p}^{HP} \quad \forall\, i, d, p \tag{24}$$

$$S_{i,d,p}^{HP\_h\_aux} \geqslant S_{i,d,p}^{HP} - ub^{HP} \cdot (1 - X_{i,d,p}^{HP\_h}) \quad \forall\, i, d, p \tag{25}$$

$$S_{i,d,p}^{HP\_h\_aux} \geqslant 0 \quad \forall\, i, d, p \tag{26}$$

Therefore, the size of the heat pump if installed needs to be larger or equal to the generated energy and between an upper and a lower bound, according to Eqs. (27)–(30):

$$S_{i,d,p}^{HP\_h\_aux} \geqslant Q_{i,d,p}^{HP\_h} \quad \forall\, i, d, p \tag{27}$$

$$S_{i}^{HP\_c\_aux} \geqslant Q_{i,d,p}^{HP\_c} \quad \forall\, i, d, p \tag{28}$$

$$S_i^{HP} \geqslant Y_i^{HP} \cdot lb^{HP} \quad \forall\, i \tag{29}$$

$$S_i^{HP} \leqslant Y_i^{HP} \cdot ub^{HP} \quad \forall\, i \tag{30}$$

The electricity absorbed for heat pumps operation is equal to:

$$E_{i,d,p}^{HP} = \frac{Q_{i,d,p}^{HP\_h}}{COP_{th}^{HP}} + \frac{Q_{i,d,p}^{HP\_c}}{COP_{c}^{HP}} \quad \forall\, i, d, p \tag{31}$$

Finally, the heat generated from heat pump, if and when is operating in heating mode, is either used in building or sent to the DHN according to (32):

$$Q_{i,d,p}^{HP\_h} = Q_{i,d,p}^{HP\_h\_build} + Q_{i,d,p}^{HP\_h\_net} \quad \forall\, i, d, p \tag{32}$$

2.1.2.4. Absorption chiller. Absorption chillers use thermal energy (heat) to provide cooling. Therefore, the constraints regarding their installation and operation are similar to the ones describing heat pumps:

$$Q_{i,d,p}^{CH\_abs} = \frac{Q_{i,d,p}^{CH\_c}}{n^{CH}} \quad \forall\, i, d, p \tag{33}$$

$$S_i^{CH} \geqslant Q_{i,d,p}^{CH\_c} \quad \forall\, i, d, p \tag{34}$$

$$S_i^{CH} \geqslant Y_i^{CHIL} \cdot lb^{CHIL} \quad \forall\, i \tag{35}$$

$$S_i^{CH} \leqslant Y_i^{CHIL} \cdot ub^{CHIL} \quad \forall\, i \tag{36}$$

2.1.2.5. Boilers. A boiler is a traditional technology used to provide heating in buildings. Constraints concerning the operation of a boiler are similar to those regarding chillers, whereas boilers do not absorb thermal energy, but they require a fuel source (e.g. natural gas or oil). Also, heating generated from boilers could be directed to the building or distributed to the DHN:

$$Z_{i,d,p}^{B} = \frac{Q_{i,d,p}^{B}}{n^{B}} \quad \forall\, i, d, p \tag{37}$$

$$S_i^{B} \geqslant Q_{i,d,p}^{B} \quad \forall\, i, d, p \tag{38}$$

$$Q_{i,d,p}^{B} = Q_{i,d,p}^{B\_build} + Q_{i,d,p}^{B\_net} \quad \forall\, i, d, p \tag{39}$$

$$S_i^{B} \geqslant Y_i^{B} \cdot lb^{B} \quad \forall\, i \tag{40}$$

$$S_i^{B} \leqslant Y_i^{B} \cdot ub^{B} \quad \forall\, i \tag{41}$$

2.1.2.6. Solar technologies. Solal photovoltaics or solar thermal collectors use solar energy to produce electricity or hot water, respectively. The constraints describing the size and operation of photovoltaics are given by Eqs. (42)–(45). Moreover, Eq. (46) states that the generated electricity from photovoltaics could be used at the building, sold to the grid or exported to the local microgrid.

$$S_i^{PV} \leqslant ub^{PV} \quad \forall\, i \tag{42}$$

$$S_i^{PV} \geqslant E_{i,d,p}^{PV} \quad \forall\, i, d, p \tag{43}$$

$$A_i^{PV} = S_i^{PV} / pv^{cof} \quad \forall\, i \tag{44}$$

$$E_{i,d,p}^{PV} \leqslant \eta^{PV} \cdot \mathrm{I}_{d,p} \cdot A_i^{PV} \quad \forall\, i, d, p \tag{45}$$

$$E_{i,d,p}^{PV} = E_{i,d,p}^{PV\_build} + E_{i,d,p}^{PV\_sell} + E_{i,d,p}^{PV\_mg} \quad \forall\, i, d, p \tag{46}$$

Solar thermal collectors generate heat to satisfy local DHW demand, which is expressed as a ratio of the total heat demand at building *i*:

$$Q_{i,d,p}^{ST} \leqslant \eta^{ST} \cdot i_{d,p}^{sol} \cdot A_i^{ST} \quad \forall\, i, d, p \tag{47}$$

$$Q_{i,d,p}^{ST} \leqslant r_{i,d,p}^{DHW} \cdot D_{i,d,p}^{heat} \quad \forall\, i, d, p \tag{48}$$

2.1.2.7. Wind turbines. Wind turbines are used to generate electricity by exploiting wind energy. They can be either vertical axis or horizontal axis. Vertical axis ones are more common and do exist in various sizes and heights. Calculating energy generation from a wind turbine requires technical knowledge of the respective turbine. In order to provide a more accurate method and be more realistic we made the assumption that the models of wind turbines considered to be installed and their respective technical characteristics are predefined. Therefore, based on the available wind turbines their respective power curves are constructed. The electricity generation from each wind turbine is calculated by using the wind speed (which is calculated from the available climate data) and provided in the form of a table.

Also, we introduced a parameter d_i^{WT} indicating if building i is available for the installation of a wind turbine ($d_i^{WT} = 1$) or not ($d_i^{WT} = 0$). That provides a more realistic representation at a neighbourhood level as the installation of a wind turbine is a more complex task and the availability of a location to host one needs to be examined. The generated electricity from the wind turbines can be used locally at the building, sold to the grid or exported to the local microgrid. Moreover, for the wind turbines installation at most one wind turbine from the available set can be installed at each building, if that building is suitable to host one, as described in Eq. (49). Therefore, the equations concerning the installation and operation of the wind turbines are:

$$\sum_{swt} Y_{i,swt}^{WT} \leqslant d_i^{WT} \quad \forall\, i \tag{49}$$

$$E_{i,d,p}^{WT} = Y_{i,swt}^{WT} \cdot wt_{i,d,p}^{elec} \quad \forall\, i, d, p \tag{50}$$

$$E_{i,d,p}^{WT} = E_{i,d,p}^{WT\_build} + E_{i,d,p}^{WT\_sell} + E_{i,d,p}^{WT\_mg} \quad \forall\, i, d, p \tag{51}$$

2.1.2.8. Storage technologies. Storage technologies are used to store heating energy or electricity for future use. In the case where a DHN or a microgrid exists, heating and electricity could be supplied from storage units. Eqs. (52) and (53) state that the rated energy of the respective technologies does not exceed its maximum value. Moreover, Eqs. (54) and (55) determine that the stored energy at the respective time period is lower than the rated capacity. Furthermore, Eqs. (56) and (57) determine the operation of the storage technologies, indicating that for each technology the total energy stored at the end of a period is equal to the energy stored at the previous time-step, plus the energy charged into storage minus the energy discharged. Finally, to apply more realistic conditions and provide initial values for the optimization procedure it is assumed that the energy stored at the first period p of day d is equal to the energy stored at the last period p of day d, as described by Eqs. (58) and (59), respectively.

$$Q_i^{ES} \leqslant ub^{ES} \quad \forall\, i \tag{52}$$

$$Q_i^{TS} \leqslant ub^{TS} \quad \forall\, i \tag{53}$$

$$E_{i,d,p}^{ES} \leqslant Q_i^{ES} \quad \forall\, i, d, p \tag{54}$$

$$E_{i,d,p}^{TS} \leqslant Q_i^{TS} \quad \forall\, i, d, p \tag{55}$$

$$E_{i,d,p}^{ES} = E_{i,d,p-1}^{ES} + \Delta_p \cdot \left(\eta_{in}^{ES} \cdot E_{i,d,p}^{ES\_in} - \frac{1}{\eta_{out}^{ES}} \cdot E_{i,d,p}^{ES\_out} \right) \quad \forall\, i, d, p \tag{56}$$

$$E_{i,d,p}^{TS} = E_{i,d,p-1}^{TS} + \delta_p \cdot (Q_{i,d,p}^{TS\_in} - Q_{i,d,p}^{TS\_out}) \quad \forall\, i, d, p \tag{57}$$

$$E_{i,d,p_1}^{ES} = E_{i,d,p_6}^{ES} \quad \forall\, i, d \tag{58}$$

$$E_{i,d,p_1}^{TS} = E_{i,d,p_6}^{TS} \quad \forall\, i, d \tag{59}$$

2.1.2.9. DHN. For the design of the DHN a first set of constraints refers to its layout to assure a realistic approach. Regarding the connections between buildings, an assumption is made that at most one pipeline can be installed between building i and building j, and that a connection cannot exist between a building and itself as described in Eqs. (60) and (61). Also, Eq. (62) states that only one heat source is allowed for each node, which means the network takes the form of a "forest" in order to avoid the production of cycles and to provide a more simplified, yet realistic approach. Moreover, to eliminate the creation of loops in the produced network Eq. (63) is introduced, which is motivated by the Travelling Salesman Problem [6]. Finally, a heating return network needs to be installed which is assumed to follow the same structure as the supply heating network, as given by Eq. (64).

$$Y_{i,j}^{HN\_SUP} + Y_{j,i}^{HN\_SUP} \leqslant 1 \quad \forall\, i, j \tag{60}$$

$$Y_{i,i}^{HN\_SUP} = 0 \quad \forall\, i, j \tag{61}$$

$$\sum_i Y_{i,j}^{HN\_SUP} \leqslant 1 \quad \forall\, j \tag{62}$$

$$O_j \geqslant O_i + 1 - |i| \cdot (1 - Y_{i,j}^{HN\_SUP}) \quad \forall\, i, j \neq i \tag{63}$$

$$Y_{i,j}^{HN\_SUP} = Y_{i,j}^{HN\_RE} \quad \forall\, i, j \tag{64}$$

In this type of decentralized network design it is assumed that each building can act both as prosumer and consumer [19]. Therefore, a building can receive thermal energy from other buildings to satisfy its demand, store it in a heat storage unit if one exists, serve as a node and send the respective amount of energy to other buildings, or export thermal energy to the network. Moreover, in this methodology we consider that the technologies which can distribute thermal energy to the DHN are the CHP, the boiler and the air/water heat pump. The operation of the DHN is described by the following Eqs. (65)–(67):

$$Q_{i,j,d,p}^{DHN} \leqslant M \cdot Y_{i,j,d,p}^{HP\_SUP} \quad \forall\, i, j, d, p \tag{65}$$

$$\sum_j Q_{i,j,d,p}^{DHN} \geqslant Q_{i,d,p}^{CHP\_net} + Q_{i,d,p}^{B\_net} + Q_{i,d,p}^{HP\_net} \quad \forall\, i, d, p \tag{66}$$

$$\sum_j Q_{i,j,d,p}^{DHN} \leqslant Q_{i,d,p}^{CHP\_net} + Q_{i,d,p}^{B\_net} + Q_{i,d,p}^{HP\_net} + \sum_j (1 - \beta^p \cdot l_{i,j}) \cdot Q_{i,j,d,p}^{DHN} \quad \forall\, i, d, p \tag{67}$$

where M, is an appropriate large number calculated as the maximum amount of heat that technologies exporting heat to the network can produce.

2.1.2.10. Electricity transfer and microgrid. Electricity generated from technologies installed at building i can be used to satisfy local demand, exported to the microgrid or sold back to the grid. Also, if the local electricity production and electricity from the microgrid cannot satisfy the demand then electricity can be bought from the national grid. Eq. (68) defines the existence of a microgrid, where N is a sufficiently large number which can be calculated as the maximum amount of electricity that could be generated throughout the year. Eq. (69) defines the electricity transfer within the microgrid in order to maintain power balance. Electricity exchange with the national grid is described by Eqs. (70)–(72), where Z is a sufficiently large number which can be estimated as the maximum amount of electricity that can be generated at a period p. Moreover, in order to promote generation from RES Eqs. (71) and (72) are used to prevent buying and selling electricity at the same period p of day d.

$$\sum_i \sum_d \sum_p [E_{i,d,p}^{WT\_mg} + E_{i,d,p}^{PV\_mg} + E_{i,d,p}^{CHP\_mg}] \leqslant N \cdot Y^{MG} \tag{68}$$

Table 1
Distances between buildings (m).

	i1	i2	i3	i4	i5	i6
i1	0	30	40	50	70	40
i2	30	0	30	20	40	80
i3	40	30	0	50	70	80
i4	50	20	50	0	20	80
i5	70	40	70	20	0	20
i6	40	80	80	80	20	0

$$(1 - etl)\cdot \sum_i [E_{i,d,p}^{WT\_mg} + E_{i,d,p}^{PV\_mg} + E_{i,d,p}^{CHP\_mg}] = \sum_i E_{i,d,p}^{MG} \quad \forall\, d, p \tag{69}$$

$$E_{i,d,p}^{sell} = E_{i,d,p}^{WT\_sell} + E_{i,d,p}^{PV\_sell} + E_{i,d,p}^{CHP\_sell} \quad \forall\, i, d, p \tag{70}$$

$$E_{i,d,p}^{sell} \leqslant Z\cdot X_{i,d,p}^{el\_sell} \quad \forall\, i, d, p \tag{71}$$

$$E_{i,d,p}^{buy} \leqslant Z\cdot (1 - X_{i,d,p}^{el\_sell}) \quad \forall\, i, d, p \tag{72}$$

2.1.2.11. Energy balances. Energy balances for electricity, heating and cooling are calculated for each building *i*, at every period *p* of a day *d*. Electricity balance is given by Eq. (73), where on the left-hand side is the sum of the electricity provided from the available technologies for local consumption, electricity discharged from the storage unit, plus the electricity that is purchased from the national grid and the electricity supplied to building *i* from the microgrid. The right-hand side consists of the sum of the electricity demand at building *i*, plus electricity absorbed by the heat pump and electricity charged to the storage unit.

$$E_{i,d,p}^{CHP\_build} + E_{i,d,p}^{PV\_build} + E_{i,d,p}^{WT\_build} + E_{i,d,p}^{ES\_out} + E_{i,d,p}^{MG} + E_{i,d,p}^{buy} = d_{i,d,p}^{elec} + E_{i,d,p}^{HP} + E_{i,d,p}^{ES\_in} \quad \forall\, i, d, p \tag{73}$$

Heating balance is calculated by Eq. (74), where the left-hand site comprises of the thermal energy generated from the installed technologies, plus the amount of energy arriving from the DHN, and the right hand side consists of the heating demand at building *i*, plus the thermal energy absorbed by the chiller, the storage or supplied to the DHN.

$$Q_{i,d,p}^{CHP} + Q_{i,d,p}^{HP\_h} + Q_{i,d,p}^{B} + Q_{i,d,p}^{ST} + Q_{i,d,p}^{TS\_out} + \sum_j (1 - \beta^p\cdot L_{i,j})\cdot Q_{i,j,d,p}^{DHN} = d_{i,d,p}^{heat} + Q_{i,d,p}^{CH\_abs} + Q_{i,d,p}^{TS\_in} + \sum_j Q_{i,j,d,p}^{DHN} \quad \forall\, i, d, p \tag{74}$$

Finally, the cooling energy balance is given by Eq. (75), in which the cooling energy produced from the heat pump and the absorption chiller must satisfy the demand at building *i*:

$$Q_{i,d,p}^{HP\_c} + Q_{i,d,p}^{CH\_c} = d_{i,d,p}^{cool} \quad \forall\, i, d, p \tag{75}$$

2.2. "Method B" for the design of a DES

"Method B" is similar to "Method A" with the main difference being that the capacities of the CHP, the heat pumps, the absorption chillers, and the boilers are predefined. The objective functions and the relative constraints are given in the following subsections. At first the sets of the technologies are defined as follows:

- Let *sco* represent the set of cogeneration technologies;
- Let *shp* represent the set of heat pumps;
- Let *sch* represent the set of absorption chillers;
- Let *sb* represent the set of boilers;

The modelling is similar, and the constraints are defined analogously to Section 2.1.2. However, constraints regarding system layout, CHP, heat pumps, chillers, boilers, electricity transfer and energy balances need to be redefined to follow the new structure.

2.2.1. Objective functions

The objective functions are again the minimization of the total

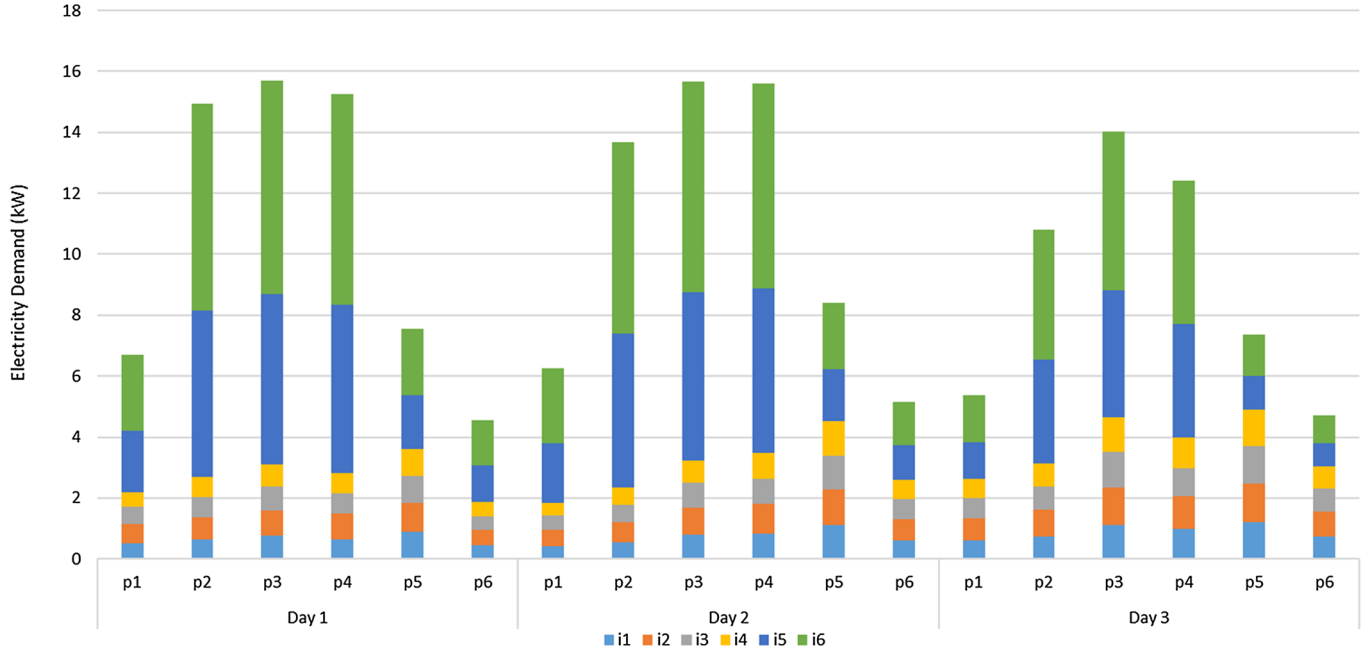


Fig. 2. Electricity demand of district buildings for the three typical days (Day 1: Winter, Day 2: Mid-season, Day 3: summer).

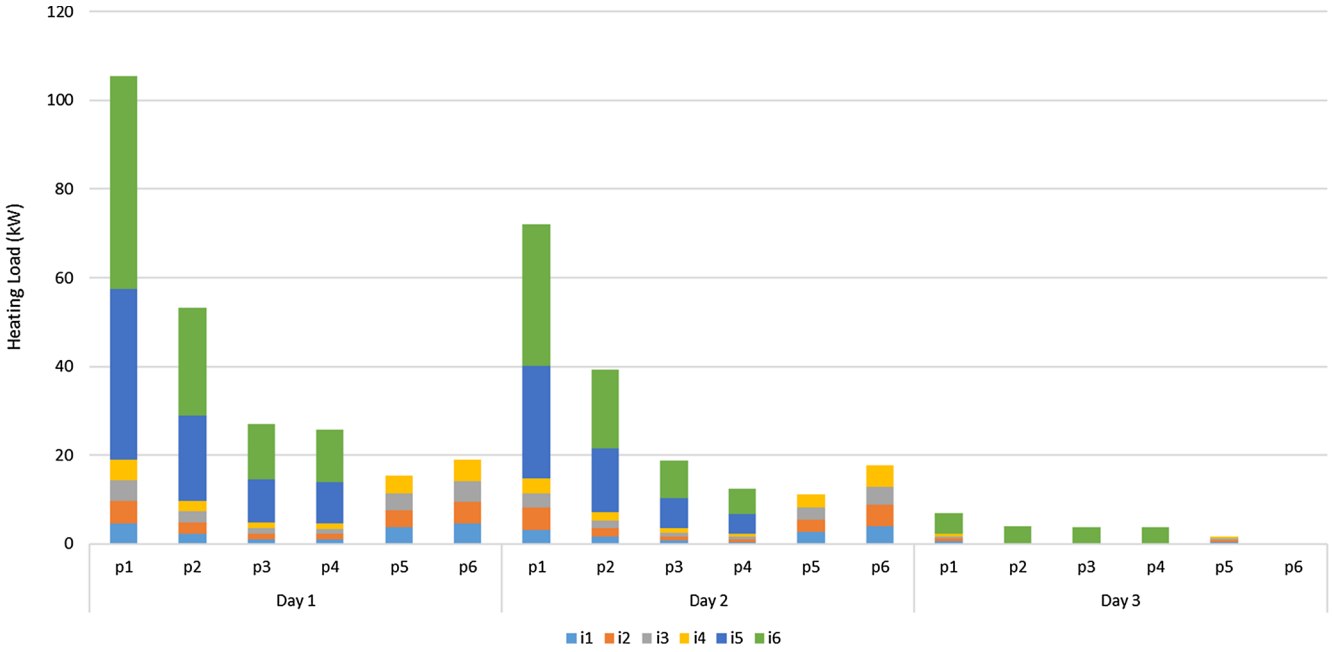


Fig. 3. Heating demand of district buildings for the three typical days (Day 1: Winter, Day 2: Mid-season, Day 3: summer).

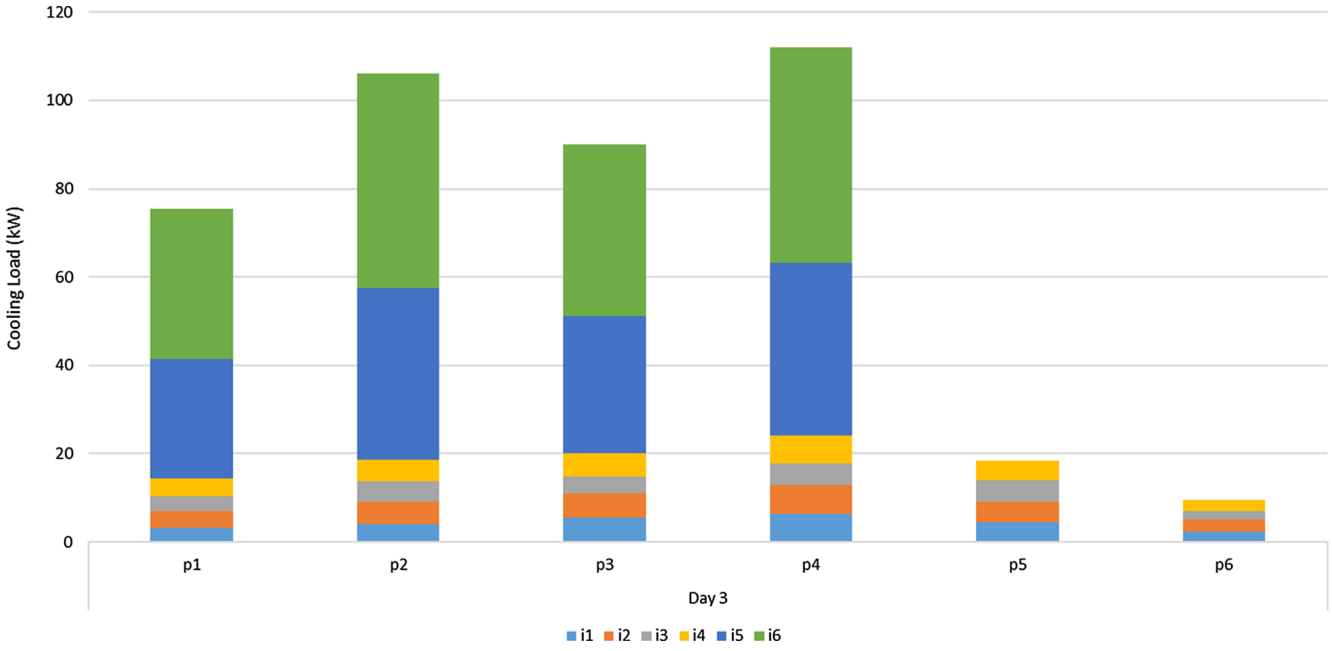


Fig. 4. Cooling demand of district buildings for Day 3: Summer.

annual cost and the minimization of the carbon emissions, as given by Eqs. (1) and (2). The model follows the same concept as described in Section 2.1.1. However, due to structural differences with the introduction of sets with predefined capacities of technologies, Eqs. (3) and (5)–(7) change as follows:

$$C^C = \sum_i \begin{bmatrix} a_n^{CHP}\cdot(c_{sco}^{CHP\_fix} + c_{sco}^{CHP\_lin}\cdot S_{i,sco}^{CHP})\cdot Y_{i,sco}^{CHP} + a_n^{HP}\cdot c_{shp}^{HP}\cdot S_{i,shp}^{HP} + \\ a_n^{CHIL}\cdot C_{sch}^{CHIL}\cdot S_{i,sch}^{CHIL} + a_n^{PV}\cdot C^{PV}\cdot S_i^{PV} + a_n^{ST}\cdot c^{ST}\cdot A_i^{ST} + \\ a_n^{B}\cdot C_{sb}^{B}\cdot S_{i,sb}^{B} + a_n^{ES}\cdot c^{ES}\cdot Q_i^{ES} + a_n^{TS}\cdot c^{TS}\cdot Q_i^{TS} + \\ a_n^{WT}\cdot(\sum_{swt} C_{swt}^{WT}\cdot S^{WT}\cdot Y_{i,swt}^{WT}) + a_n^{MG}\cdot c^{MG}\cdot Y^{MG} + \\ a_n^{P}\cdot c^{p}\cdot l_{i,j}\cdot(Y_{i,j}^{HN\_SUP} + Y_{i,j}^{HN\_RET}) \end{bmatrix} \quad (76)$$

$$C^O = \sum_i \sum_d \sum_p \Delta_p\cdot N_d\cdot \begin{bmatrix} c^{ng}\cdot(Z_{i,sco,d,p}^{CHP} + Z_{i,sb,d,p}^{B}) + c_{d,p}^{el\_buy}\cdot E_{i,d,p}^{el\_grid} \\ -(c^{PV\_sell}\cdot E_{i,d,p}^{PV\_sell} + c^{WT\_sell}\cdot E_{i,d,p}^{WT\_sell} + c^{CHP\_sell}\cdot E_{i,sco,d,p}^{CHP\_sell}) \end{bmatrix} \quad (77)$$

$$C^M = \sum_i \sum_d \sum_p \begin{bmatrix} \delta_p\cdot n_d\cdot\mu_{sco}^{CHP}\cdot E_{i,sco,d,p}^{CHP} + \mu_{shp}^{HP}\cdot E_{i,shp,d,p}^{HP} + \mu_{sch}^{CHIL}\cdot Q_{i,sch,d,p}^{CHIL} \\ + \mu_{sb}^{B}\cdot Q_{i,sb,d,p}^{B} + (\sum_{swt}\mu_{swt}^{WT}\cdot E_{i,d,p}^{WT}\cdot Y_{i,swt}^{WT}) + \mu^{TS}\cdot E_{i,d,p}^{TS} \\ + \mu^{PV}\cdot S_{i,d,p}^{PV} + \mu^{ST}\cdot S_{i,d,p}^{ST} \end{bmatrix} \quad (78)$$

$$CARBON^F = \sum_i \sum_d \sum_p [\delta_p\cdot n_d\cdot(Z_{i,sco,d,p}^{CHP} + Z_{i,sb,d,p}^{B})\cdot f^{ng}] \quad (79)$$

2.2.2. Constraints

2.2.2.1. System layout. At first it needs to be imposed that regarding

Table 2
Summary of the available technologies and their respective technical characteristics.

Technology	Method "A"		Method "B"	
	Capacity	Efficiency	Capacity bounds	Efficiency
CHP	5 kW	0.35 (*el.*) 0.50 (*th.*)	5–100 kW	0.38 (*el.*)
	20 kW	0.38 (*el.*) 0.52 (*th.*)		0.52 (*th.*)
Heat pumps	10 kW 50 kW	$COP^h = 3.5$ $COP^c = 3.0$	5–50 kW	$COP^h = 3.5$ $COP^c = 3.0$
Chillers	10 kW 50 kW	0.85 0.87	5–50 kW	0.87
Boilers	10 kW 30 kW	0.88 0.90	5–50 kW	0.88
Wind Turbines	10 kW 20 kW	–	10 kW 20 kW	–
Photovoltaics	≤10 kW	0.16	≤10 kW	0.16
Solar thermal	–	0.6	–	0.6
Thermal storage	≤100 kWh	–	≤100 kWh	–
Electricity storage	≤100 kWh	0.9 *(in)* 0.85 *(out)*	≤100 kWh	0.9 *(in)* 0.85 *(out)*

Table 3
Economic data of the available technologies.

Technology	Capital cost	Maintenance cost
CHP	C_{fix}: 1000 € C_{lin}: 500 €/kW	0.027 €/kWh
Heat pumps	545 €/kW	0.001 €/kWh
Chillers	850 €/kW	0.001 €/kWh
Boilers	100 €/kW	0.0027 €/kWh
Wind turbines	3000 €/kW	0.01 €/kWh
Photovoltaics	2000 €/kW	14 €/kW/year
Solar thermal	700 €/kW	18 €/m^2/year
Thermal storage	60 €/kWh	0.01 €/kWh
Electricity storage	500 €/kWh	–
Pipe	100 €/m	–
Microgrid controller	1500 €	–

Table 4
Electricity purchase price in (€/kWh) for each typical day and time period.

Electricity purchase price (€/kWh)	p1	p2	p3	p4	p5	p6
d1: Winter	0.0778	0.0946	0.0946	0.0812	0.0946	0.0946
d2: Mid-season	0.0863	0.0946	0.0946	0.0879	0.0946	0.0795
d3: Summer	0.0946	0.0946	0.0946	0.0946	0.0946	0.0647

CHP and boilers at most one unit of their respective sets can be installed at each building *i*:

$$\sum_{sco} Y^{CHP}_{i,sco} \leqslant 1 \quad \forall\, i \tag{80}$$

$$\sum_{sb} Y^{B}_{i,sb} \leqslant 1 \quad \forall\, i \tag{81}$$

As far as heat pumps and chillers are concerned, Eq. (9) applies in this method too:

$$\sum_{shp} Y^{HP}_{i,shp} + \sum_{sch} Y^{CHIL}_{i,sch} \leqslant 1 \quad \forall\, i \tag{82}$$

Constraint regarding solar technologies layout is applied as described in Section 2.1.2.1.

2.2.2.2. CHP installation and operation. CHP modelling follows the same principles as described in Section 2.1.2.2:

$$X^{CHP}_{i} \leqslant Y^{CHP}_{i} \quad \forall\, i \tag{83}$$

$$E^{CHP}_{i,sco,d,p} = E^{CHP\_build}_{i,sco,d,p} + E^{CHP\_sell}_{i,sco,d,p} + E^{CHP\_mg}_{i,sco,d,p} \quad \forall\, i, sco, d, p \tag{84}$$

$$E^{CHP}_{i,sco,d,p} = Q^{CHP}_{i,sco,d,p} \cdot \frac{n^{CHP\_el}_{sco}}{n^{CHP\_th}_{sco}} \quad \forall\, i, sco, d, p \tag{85}$$

$$Q^{CHP}_{i,sco,d,p} = Q^{CHP\_build}_{i,sco,d,p} + Q^{CHP\_net}_{i,sco,d,p} \quad \forall\, i, sco, d, p \tag{86}$$

$$Z^{CHP}_{i,sco,d,p} = \frac{E^{CHP}_{i,sco,d,p}}{n^{CHP\_el}_{sco}} \quad \forall\, i, sco, d, p \tag{87}$$

$$P^{CHP}_{i,sco} \cdot k^{CHP}_{sco} \cdot X^{CHP}_{i,sco,d,p} \leqslant E^{CHP}_{i,sco,d,p} \leqslant P^{CHP}_{i,sco} \cdot X^{CHP}_{i,sco,d,p} \quad \forall\, i, sco, d, p \tag{88}$$

2.2.2.3. Heat pumps. Heat pumps modelling is simpler in this method compared to Method "A". In this case there are no non-linear terms and all equations can be expressed through MILP modelling without applying any linearization techniques:

$$X^{HP\_h}_{i,shp,d} + X^{HP\_c}_{i,shp,d} \leqslant Y^{HP}_{i,shp} \quad \forall\, i, shp, d \tag{89}$$

$$\sum_{p} X^{HP\_h}_{i,shp,d,p} \leqslant |p| \cdot X^{HP\_h}_{i,shp,d} \quad \forall\, i, shp, d \tag{90}$$

$$\sum_{p} X^{HP\_c}_{i,shp,d,p} \leqslant |p| \cdot X^{HP\_c}_{i,shp,d} \quad \forall\, i, d \tag{91}$$

$$E^{HP\_h}_{i,shp,d,p} = \frac{Q^{HP\_h}_{i,shp,d,p}}{COP^{HP}_{th}} + \frac{Q^{HP\_c}_{i,shp,d,p}}{COP^{HP}_{c}} \quad \forall\, i, shp, d, p \tag{92}$$

$$Q^{HP\_h}_{i,shp,d,p} \leqslant X^{HP\_h}_{i,shp,d,p} \cdot P^{HP}_{i,shp} \quad \forall\, i, shp, d, p \tag{93}$$

$$Q^{HP\_c}_{i,shp,d,p} \leqslant X^{HP\_c}_{i,shp,d,p} \cdot P^{HP}_{i,shp} \quad \forall\, i, shp, d, p \tag{94}$$

$$Q^{HP\_h}_{i,shp,d,p} = Q^{HP\_h\_build}_{i,shp,d,p} + Q^{HP\_h\_net}_{i,shp,d,p} \quad \forall\, i, shp, d, p \tag{95}$$

2.2.2.4. Absorption chillers. Constraints regarding the installation and operation of absorption chillers are described as follows:

$$Q^{CH\_abs}_{i,sch,d,p} = \frac{Q^{CH\_c}_{i,sch,d,p}}{n^{CH}_{sch}} \quad \forall\, i, sch, d, p \tag{96}$$

$$X^{CH}_{i,sch,d,p} \leqslant Y^{CH}_{i,sch,d,p} \quad \forall\, i, sch, d, p \tag{97}$$

$$Q^{CH\_c}_{i,sch,d,p} \leqslant P^{CH}_{i,sch,d,p} \cdot X^{CH}_{i,sch,d,p} \quad \forall\, i, sch, d, p \tag{98}$$

2.2.2.5. Boilers. Equations representing boiler installation and operation are:

$$Z^{B}_{i,sb,d,p} = \frac{Q^{B}_{i,sb,d,p}}{n^{B}_{sb}} \quad \forall\, i, sb, d, p \tag{99}$$

$$X^{B}_{i,sb,d,p} \leqslant Y^{B}_{i,sb,d,p} \quad \forall\, i, sb, d, p \tag{100}$$

$$Q^{B}_{i,sb,d,p} \leqslant X^{B}_{i,sb,d,p} \cdot P^{B}_{i,sb,d,p} \quad \forall\, i, sb, d, p \tag{101}$$

$$Q^{B}_{i,sb,d,p} = Q^{B\_build}_{i,sb,d,p} + Q^{B\_net}_{i,sb,d,p} \quad \forall\, i, sb, d, p \tag{102}$$

2.2.2.6. Solar technologies. Constraints described in Section 2.1.2.6 apply.

2.2.2.7. Wind turbines. Constraints described in Section 2.1.2.7 apply

2.2.2.8. Storage technologies. Constraints apply in Section 2.1.2.8 apply.

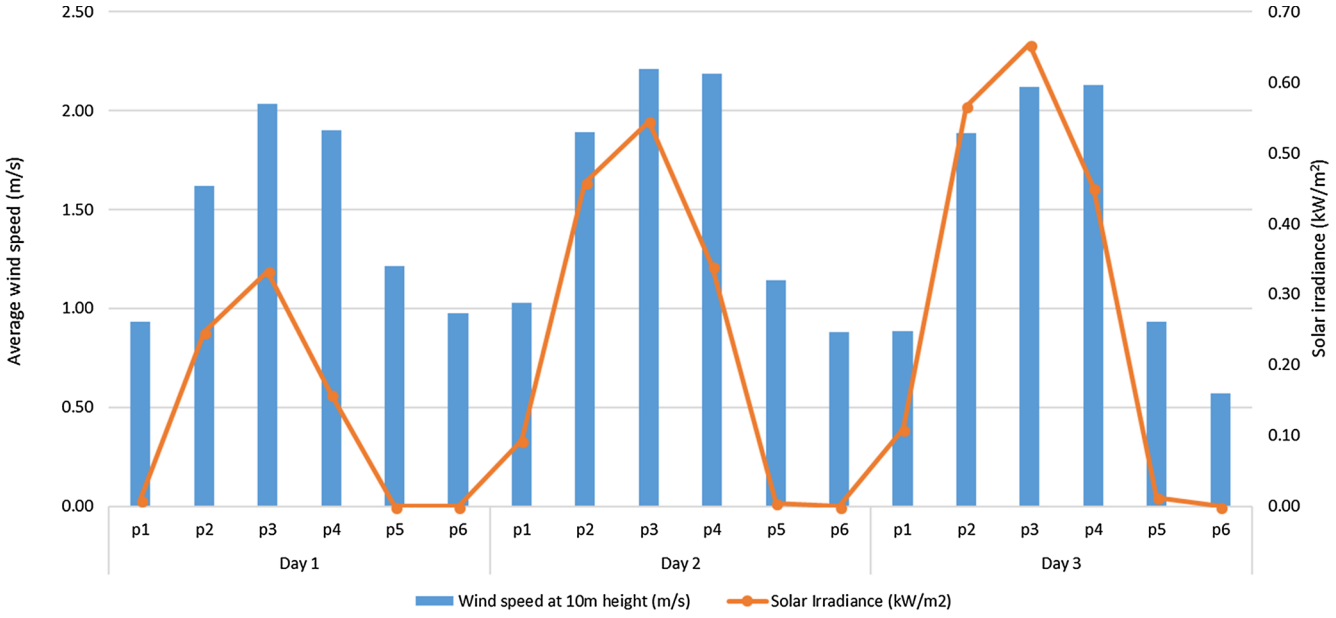


Fig. 5. Average wind speed and solar irradiation for the three typical days, for all periods.

Table 5
Area for solar technologies and parameter for wind turbines ($d_{iWT} = 1$ means suitable for WT).

Building	A_i (m^2)	d_i^{WT}
i1	75	0
i2	80	0
i3	67	0
i4	70	0
i5	90	1
i6	100	0

2.2.2.9. DHN. Constraints regarding DHN are the same as those described in Section 2.1.2.9, except constraints (66) and (67), which are defined as:

$$\sum_{j} Q_{i,j,d,p}^{DHN} \geqslant \sum_{sgc} Q_{i,sgc,d,p}^{CHP\_net} + \sum_{sb} Q_{i,sb,d,p}^{B\_net} + \sum_{shp} Q_{i,shp,d,p}^{HP\_net} \quad \forall\, i,\, d,\, p \tag{103}$$

$$\sum_{j} Q_{i,j,d,p}^{DHN} \leqslant \sum_{sgc} Q_{i,sgc,d,p}^{CHP\_net} + \sum_{sb} Q_{i,sb,d,p}^{B\_net} + \sum_{shp} Q_{i,shp,d,p}^{HP\_net} + \sum_{j} (1 - \beta^{p} \cdot l_{i,j}) \cdot Q_{i,j,d,p}^{DHN} \quad \forall\, i,\, d,\, p \tag{104}$$

2.2.2.10. Electricity transfer. Regarding electricity transfer only Eqs. (68)–(70) change form and are defined as:

$$\sum_{i} \sum_{d} \sum_{p} \left[E_{i,d,p}^{WT\_mg} + E_{i,d,p}^{PV\_mg} + \sum_{sco} E_{i,sco,d,p}^{CHP\_mg} \right] \leqslant N \cdot Y^{MG} \tag{105}$$

$$(1 - etl) \cdot \sum_{i} \left[E_{i,d,p}^{WT\_mg} + E_{i,d,p}^{PV\_mg} + \sum_{sco} E_{i,d,p}^{CHP\_mg} \right] = \sum_{i} E_{i,d,p}^{MG} \quad \forall\, d,\, p \tag{106}$$

$$E_{i,d,p}^{sell} = E_{i,d,p}^{WT\_sell} + E_{i,d,p}^{PV\_sell} + E_{i,sco,d,p}^{CHP\_sell} \quad \forall\, i,\, sco,\, d,\, p \tag{107}$$

It is noted that Eqs. (71) and (72) still apply.

2.2.2.11. Energy balances. Energy balances for electricity, heating and cooling are given by Eqs. (108)–(110), respectively:

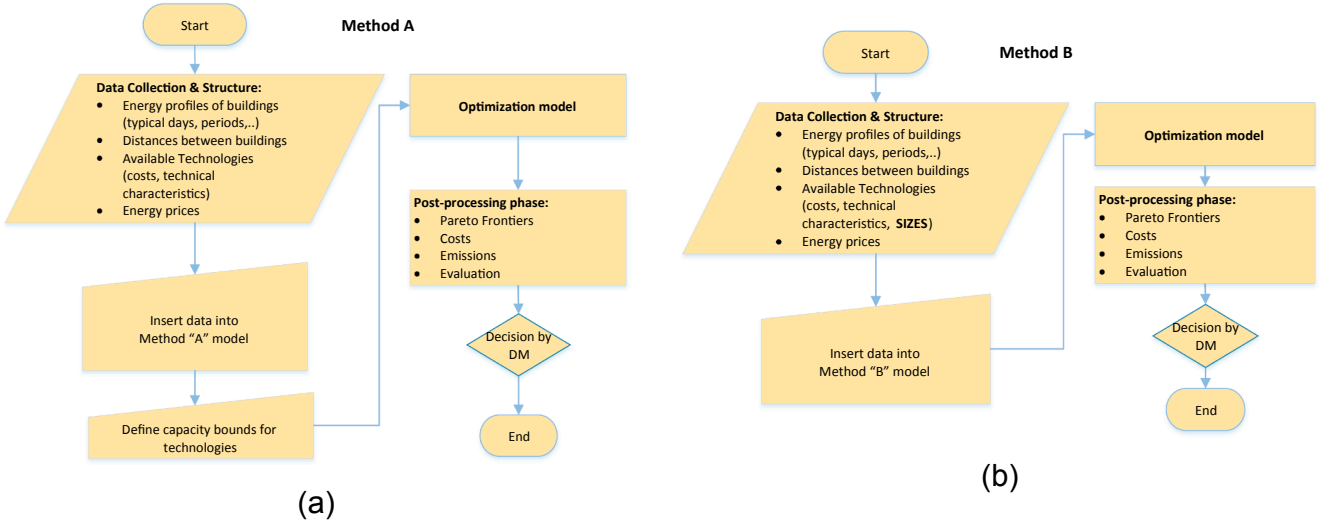


Fig. 6. Technical route diagram for "Method A" and "Method B"

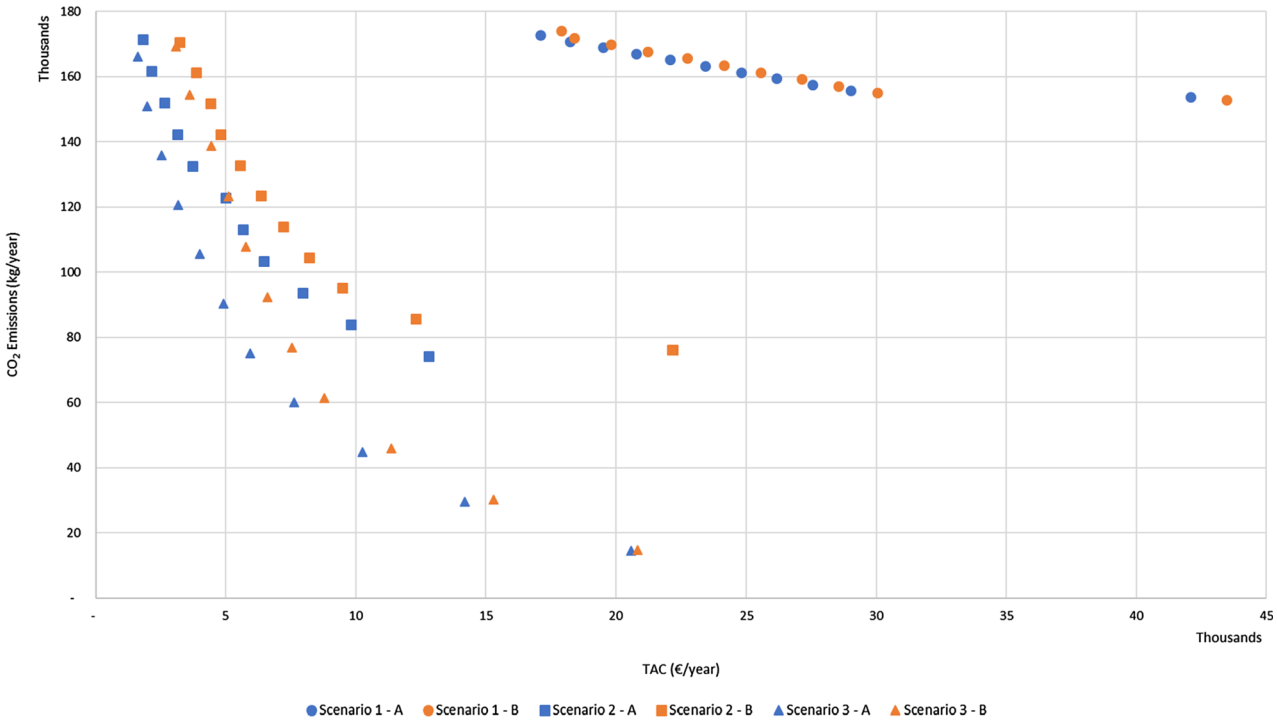


Fig. 7. Pareto fronts for the three scenarios in “Method A” and “Method B”.

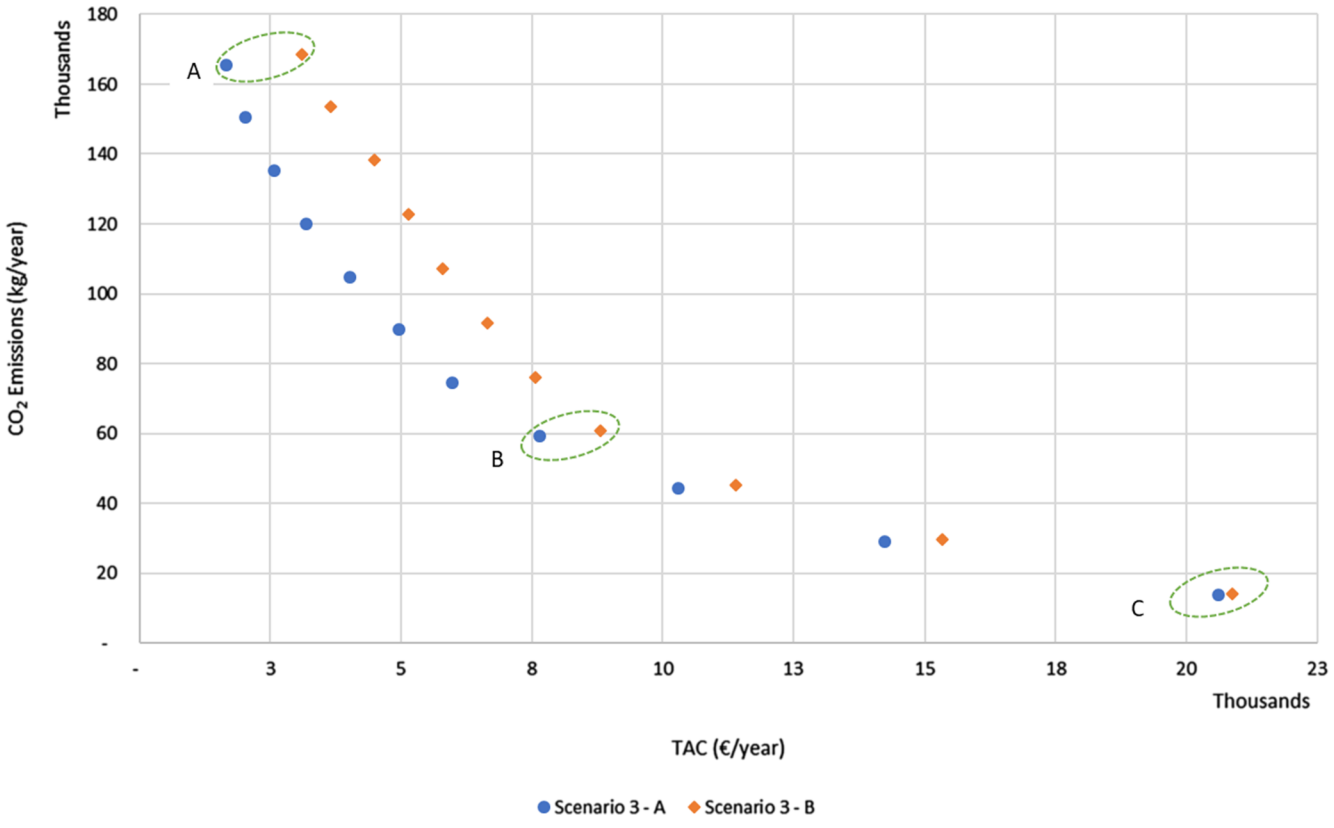


Fig. 8. Pareto frontiers for scenario 3 in “Method A” and “Method B”.

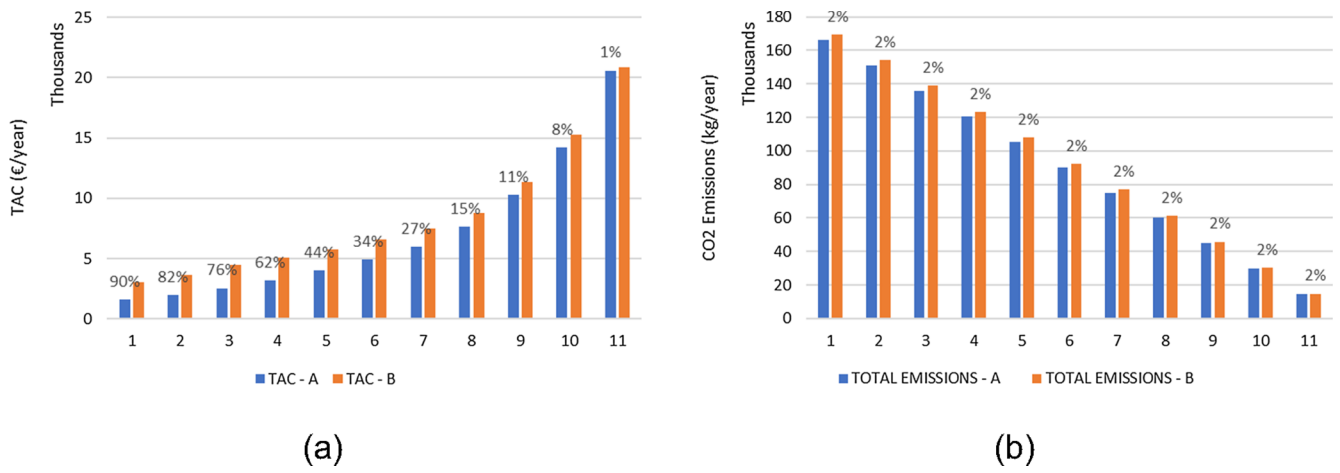


Fig. 9. Difference in values of objective functions in "Method B" compared to "Method A" for Scenario 3: (a) Comparison of TAC and (b) Comparison of carbon emissions.

$$\sum_{sco} E^{CHP\_build}_{i,sco,d,p} + E^{PV\_build}_{i,d,p} + E^{WT\_build}_{i,d,p} + E^{ES\_out}_{i,d,p} + E^{MG}_{i,d,p} + E^{buy}_{i,d,p} = D^{elec}_{i,d,p} + \sum_{shp} E^{HP}_{i,d,p} + E^{ES\_in}_{i,d,p} \quad \forall\, i, d, p \tag{108}$$

$$\sum_{sco} Q^{CHP}_{i,sco,d,p} + \sum_{shp} Q^{HP\_h}_{i,shp,d,p} + \sum_{sb} Q^{B}_{i,sb,d,p} + Q^{ST}_{i,d,p} + Q^{TS\_out}_{i,d,p} + \sum_{j} (1-\beta^{p\cdot l_{i,j}}) \cdot Q^{DHN}_{i,j,d,p} = D^{heat}_{i,d,p} + \sum_{sch} Q^{CH\_abs}_{i,sch,d,p} + Q^{TS\_in}_{i,d,p} + \sum_{j} Q^{DHN}_{i,j,d,p} \quad \forall\, i, d, p \tag{109}$$

$$\sum_{shp} Q^{HP\_c}_{i,shp,d,p} + \sum_{sch} Q^{CH\_c}_{i,sch,d,p} = D^{cool}_{i,d,p} \quad \forall\, i, d, p \tag{110}$$

3. Case study

The application of the proposed methodologies is shown by means of a case study (one for each method).

3.1. Input data

The two methodologies were applied to a complex of six buildings located in Athens, Greece. Buildings 1–4 are typical residential dwellings, building 5 is a small commercial building and building 6 is a school. The distances between the buildings are given in Table 1. In this analysis, a year is divided into three typical days each one representing a season, winter (day 1, November – February), mid-season (day 2, March – May, October) and summer (day 3, June- September). A typical day consists of six typical periods (h7–h9, h9–h12, h12–h13, h13–h18, h18–h22, h22–h7). As aforementioned, the model is generic, and the decision maker could set up a more detailed representation of the year. However, several studies have shown that this level of analysis is adequate for this type of simulations. A more detailed approach would result in a more complex system with higher computational intensity which would not change the results significantly [12].

The energy loads for the buildings for the three respective days are depicted in Figs. 2–4. Data for the energy loads were taken from literature (e.g. [6]) or were calculated approximately based on the energy load pattern of each building type and its respective size. The detailed calculation of the energy loads is out of the scope of this paper.

The technologies into consideration and their respective capacities are presented in Table 2. The capital and maintenance costs for each technology are presented in Table 3. The lifetime of CHP, heat pumps, chillers, boilers, wind turbines, photovoltaics and solar thermal is considered to be 20 years. Electricity and thermal storage have a lifetime of 15 and 30 years respectively, and finally, pipes have a lifetime of 30 years. Discount rate is set to be 7.5%.

The fuel cost (natural gas) is set at 0.054 €/kWh which is calculated for Greek market [7]. The cost of buying electricity from the grid is calculated for each period based on the residential tariff [24]. However, as the hours of the residential tariff do not coincide with the periods set in this test case, the tariffs used were calculated as weighted averages of the hours of each period and the respective tariff and presented in Table 4. The price for selling electricity to the grid is set at 0.156 €/kWh for photovoltaics, at 0.08785 €/kWh for electricity from CHP, and at 0.25 €/kWh for wind turbines, respectively [25]. The carbon emission factor for natural gas consumption is 0.184 kg/kWh [7]. The carbon emission factor for electricity generation from the grid is 1.12 €/kWh [24].

Regarding climate data, such as solar irradiance and wind speed those were taken from available data for the year 2015 from a meteorological station operated by NTUA. Values were divided for each month and hour, and the values for the typical days and periods used in this case study were then calculated as the respective average. Solar irradiance and wind speed for this area of Athens are depicted in Fig. 5.

The available surface for the installation of solar technologies and the parameter indicating the suitability of buildings for installation of wind turbines are presented in Table 5.

The following assumptions were also made:

- CHP operates at a minimum part load of 50%. This value is consistent with literature as it is considered that above this value the efficiency of the CHP remains constant [19]. Also, CHP can be turned on and off without constraints.
- Starting-ups and shutting-downs of the installed technologies are controlled; therefore, they are at operational level without any time delay.
- The COP of heat pumps is considered constant for all typical days. Typically, COP is calculated based on external temperatures, however its detailed calculation is considered outside of the scope of this paper.
- Electrical grid has large capacity to satisfy the demand if needed and integrate the DES without any stability issues. The same assumption applies when electricity from DES is injected in the microgrid.
- Photovoltaics are installed and operate at an optimal angle.
- Heating losses are proportional to the distance between buildings and are equal to 0.00015 m^{-1} [12].

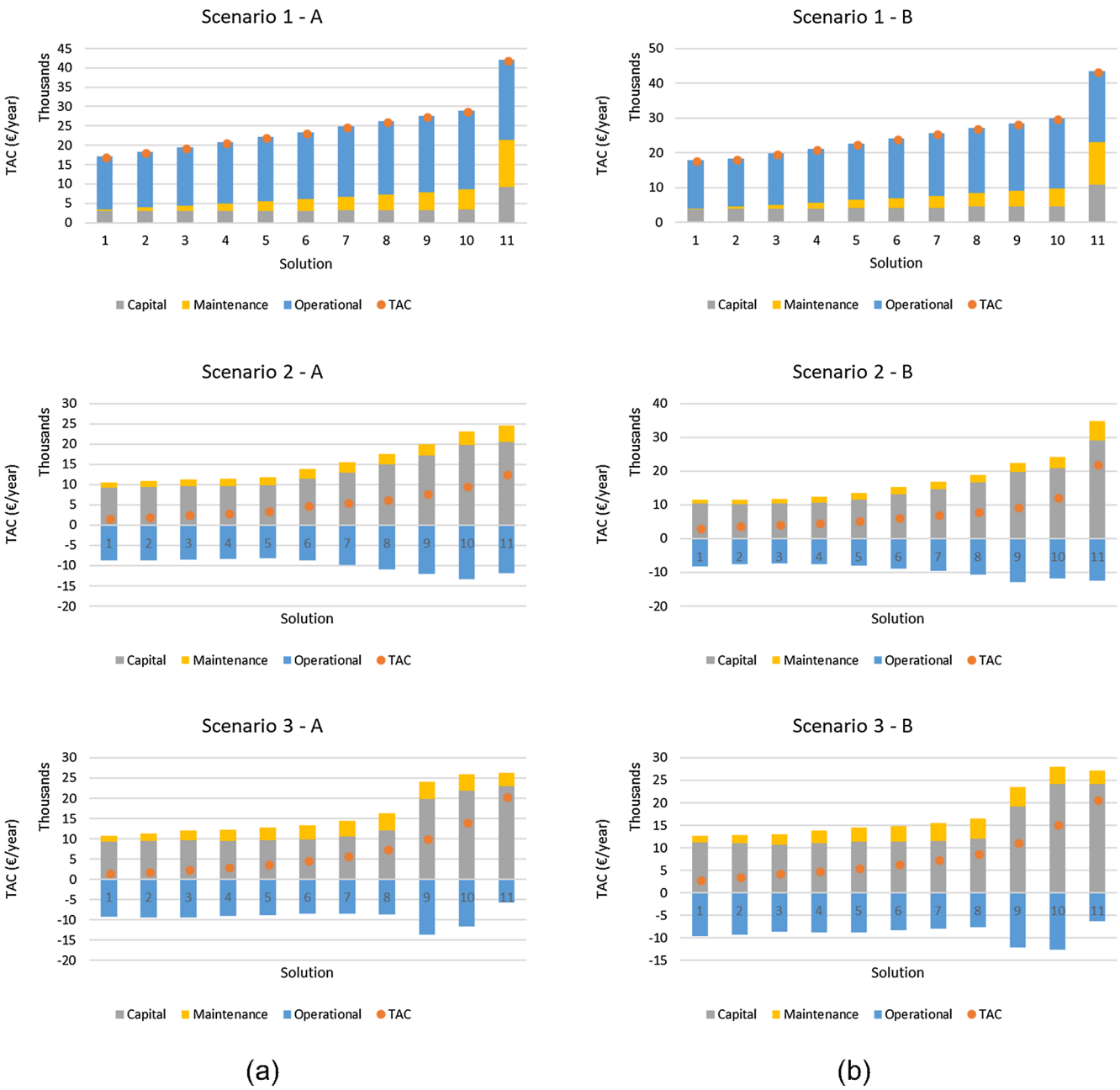


Fig. 10. A detailed breakdown of TAC equations components for (a) "Method A" and (b) "Method B", respectively.

- Transmission losses between microgrid are equal to 1% [7].
- Capital costs include investment and installation cost.
- Values regarding climate data and fuel prices are considered to be known with certainty and remain constant for all the lifetime of the DES.

3.2. Scenarios

Besides the implementation of the two methodologies into a case study, three different scenarios were defined in order to assess the results and provide a more accurate output regarding how the integration of DES offers a more economic and environmentally friendly solution in terms of designing future energy systems. Therefore, the three scenarios are defined as follows:

- *Scenario 1 – Business-as-usual (BAU):* This is the conventional scenario where heating demand in buildings is satisfied by boilers and cooling by air condition units. Also, solar thermal collectors are used which is considered conventional technology in Greece. Electricity is bought from the national grid.
- *Scenario 2 – Renewables:* The same as scenario 1 (air condition units are replaced with air/water heat pumps), plus renewables (pv and wind turbines), absorption chillers and cogeneration technologies. Also, buildings can exchange electricity with the grid (buying/selling).
- *Scenario 3 – DES:* The same as scenario 2, plus the storage technologies, the microgrid and the DHN.

4. Results

In this section the results of the two methods for the three scenarios are presented. The multi-objective optimization models have been implemented using the AUGMECON2 method [22] in GAMS and the GUROBI solver has been applied to solve them on a PC with a 3 GHz

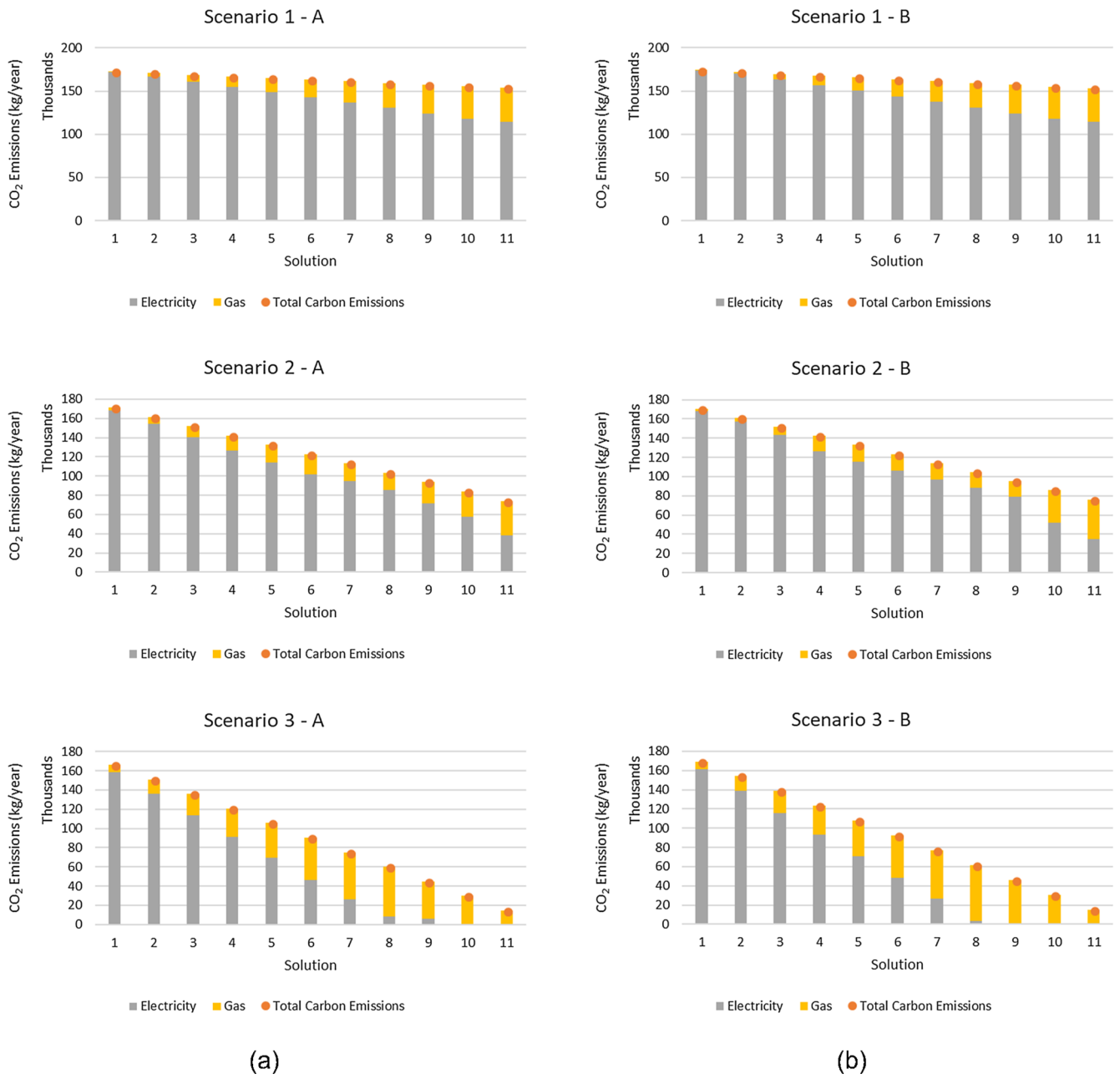


Fig. 11. A detailed breakdown of carbon emissions equations components for (a) “Method A” and (b) “Method B”, respectively.

processor and 12 GB RAM. A flowchart for the use of “Method A” and “Method B” is presented in Fig. 6.

The results for Scenario 1 – Scenario 3, for “Method A” and “Method B” are depicted in Fig. 7.

4.1. Results of “Method A”

At first it can be noticed that for all scenarios the TAC and the carbon emissions are conflicting objectives, i.e. the higher the TAC is the lower the carbon emissions are. Scenario 1 (BAU) is the most expensive solution, both in terms of cost and emissions. It can also be observed that scenario 1 does not offer a typical Pareto frontier, which can be attributed to the absence of degrees of freedom. Moreover, regarding the comparison between scenario 2 and scenario 3, it seems that scenario 3 offers better solutions. More specifically, scenario 3 is the one with the lowest TAC and carbon emissions. Analytically, scenario 2 provides solutions with TAC between some 1803 and 12,794 €/year and carbon emissions between 74,158 and 171,421 kg/year. On the other hand, in scenario 3 TAC is between 1614 and 20,575 €/year and carbon emissions between 14,456 and 166,161 kg/year. It can be concluded that the addition of storage units, microgrid and the DHN network further drives emissions down, and more specifically provides solutions where emissions are five times lower (best case solution of carbon emissions in scenario 2 compared to scenario 3).

4.2. Results of “Method B”

It can be observed that the results for the three scenarios follow a similar pattern to “Method A”. Specifically, scenario 1 provides the solutions with the higher TAC and carbon emissions, followed by scenario 2 and scenario 3, which is the one with the best results. In scenario 2 of this method, TAC is between 3212 and 22,170 €/year, while

Table 6
Detailed configuration of optimal solutions for “Method A” and “Method B”

Scenario 1

	HP (kW)		BOILER (kW)		ST (m^2)	
	A	B	A	B	A	B
1	112	140	25	50	10	0
2	112	140	25	50	14	14
3	112	140	25	50	14	14
4	112	140	25	50	14	14
5	112	140	25	70	14	14
6	112	140	25	70	14	14
7	112	140	30	70	14	14
8	112	140	35	100	14	14
9	112	140	44	100	14	14
10	112	140	60	100	14	14
11	112	140	80	180	392	392

Scenario 2

	CHP (kW)		HP (kW)		ACH (kW)		WT (kW)		BOILER (kW)		PV (kW)		ST (m^2)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	9	5	112	140	0	0	10	10	25	50	0	0	0	0
2	9	5	112	140	0	0	10	10	25	40	0	0	4	0
3	14	5	112	140	0	0	10	10	20	40	0	1	0	0
4	14	10	112	140	0	0	10	10	20	40	0	0	0	0
5	12	10	112	140	0	0	10	10	20	40	1	5	0	0
6	17	10	112	140	0	0	10	10	20	40	8	13	0	0
7	12	10	112	140	0	0	10	10	20	40	17	21	12	0
8	12	10	112	140	0	0	10	10	20	40	28	30	0	0
9	17	10	112	140	0	0	10	10	20	40	38	47	0	0
10	23	30	112	140	0	0	10	10	20	40	47	45	14	0
11	33	30	112	140	0	0	10	10	26	180	47	60	14	59

Scenario 3

	CHP (kW)		HP (kW)		ACH (kW)		WT (kW)		BOILER (kW)		PV (kW)		ST (m^2)		ES (kWh)		TS (kWh)		DHN		MG	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	5	5	112	140	0	0	10	10	5	0	0	0	0	0	0	0	3	7	3	5	0	1
2	10	15	106	120	6	20	10	10	10	0	0	0	0	0	0	0	6	0	1	3	1	1
3	11	10	101	120	11	20	10	10	5	20	0	0	3	0	0	0	2	1	3	2	1	1
4	13	25	101	90	12	50	10	10	5	40	0	0	0	3	0	0	0	11	2	2	1	1
5	14	25	99	100	13	40	10	10	0	0	0	0	0	0	0	0	10	36	3	5	1	1
6	17	25	94	100	18	40	10	10	5	0	0	0	0	0	0	0	6	36	3	5	1	1
7	20	25	94	100	18	40	10	10	0	0	3	0	0	3	0	0	3	59	4	5	1	1
8	33	35	73	80	39	60	10	10	2	0	8	1	9	11	0	0	10	56	5	5	1	1
9	21	25	94	100	18	40	10	10	20	0	49	37	0	11	0	0	12	95	3	5	1	1
10	16	25	97	120	18	20	10	10	25	0	60	60	12	12	0	0	16	108	3	4	1	1
11	18	20	109	120	11	20	10	10	20	10	60	60	14	16	7	9	62	81	3	5	1	1

carbon emissions are between 76,271 and 170,607 kg/year. In scenario 3 TAC is lower and between 3074 and 20,846 €/year, and carbon emissions between 14,794 and 169,248 kg/year.

4.3. Comparison – discussion

In both methods scenario 2 offers better solutions compared to scenario 1, and scenario 3 better solutions compared to scenario 2, especially for carbon emissions. Scenario 3 can provide a reduction to carbon emissions up to 81%, compared to scenario 2 in each method. Regarding the best solution for total annual cost, in “Method A” scenario 3 provides an 11% reduction compared to scenario 2, while in “Method B” a 4% reduction.

To provide a more sufficient understanding and a better comparison between the two methodologies, in Fig. 8 the Pareto frontiers for scenario 3 – DES are presented. It can be seen more clearly that “Method A” provides better solutions compared to “Method B”. In each of these solutions, the configuration of the DES and the operational profile of the technologies is different. Computational time for scenario 3 in “Method A” and “Method B” is 50 min and 40 min respectively. It has been observed that the most computationally intensive part is the optimization of the second objective, carbon emissions. Computational times for Scenario 1 and 2 are much lower. Specifically, 3 and 9 s for “Method A”, and 3 and 7 s for “Method B”, respectively. It is clear that the computational time increases dramatically due to the addition of more technologies and especially storage, DHN and microgrid which make the models dramatically more complex (from some seconds the computational time explodes to almost an hour).

A comparison of the differences in the results of the objective functions in Scenario 3 is presented in more detail in Fig. 9. It can be seen that the major differences between the two methods refer to the first objective function (cost). The differences are higher in the first solution (minimizing cost) where “Method B” has a higher TAC by some 90% compared to “Method A”. As solutions move towards decreasing

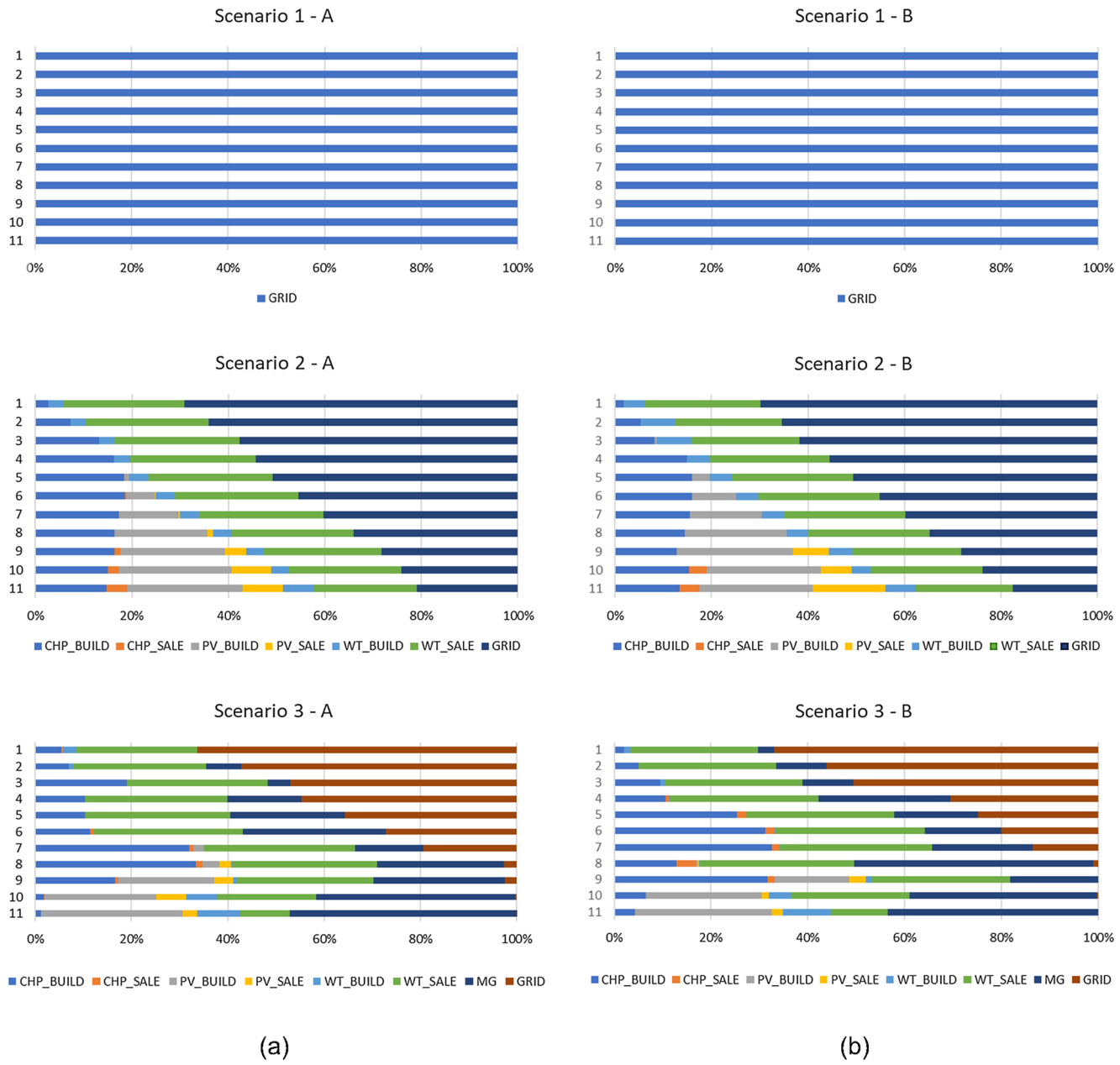

Scenario 1 - A
Scenario 1 - B
Scenario 2 - A
Scenario 2 - B
Scenario 3 - A
Scenario 3 - B
GRID
CHP_BUILD CHP_SALE PV_BUILD PV_SALE WT_BUILD WT_SALE GRID
CHP_BUILD CHP_SALE PV_BUILD PV_SALE WT_BUILD WT_SALE MG GRID
0% 20% 40% 60% 80% 100%
(a)
(b)

Fig. 12. Electricity supply mix for Scenarios 1, 2 and 3, for: (a) “Method A” and (b) “Method B”.

carbon emissions both methods seem to provide similar results, reaching a difference as low as 1% in the final solution. Regarding differences in carbon emissions “Method B” again provides solutions with higher value, however in this case results are slightly higher in the order of 2% for all solutions.

A detailed breakdown of the TAC for each method and scenario is presented in Fig. 10. In both methods solutions follow a similar pattern, with the capital cost being the largest component, while on the other hand the maintenance cost has the less impact. It is also noted that in all solutions in Scenarios 2 and 3 the operational cost is negative, which means there is a profit that could be attributed to electricity sales from excess electricity sold to the grid from renewables or CHP units installed. Also, as solutions move towards the carbon emissions objective the capital cost gets higher, leading to more expensive solutions and showing that cost and emissions are conflicting objectives.

In Fig. 11 solutions regarding the carbon emissions components are presented. It can be seen that as solutions move towards the minimization of CO_2, the contribution of fuel-based emissions (natural gas) gets higher. This is due to the impact of carbon emissions factor, which is lower for the natural gas compared to emissions attributed to electricity from the Greek national grid.

Each solution in each method and scenario besides different values of objective functions, has a different configuration and operational profile of the energy system. A detailed analysis of the configuration in each optimal solution is presented in Table 6 with the following results: (a) total capacity installed of each technology, (b) number of DHN links and (c) installation of a microgrid.

In Scenario 1 all solutions have a similar configuration for both methods, except the final solution which is the optimal solution for minimizing carbon emissions. The reason for this is the small number of available technologies, hence there are less degrees of freedom. On the other hand, in scenarios 2 and 3 each solution has a different optimal configuration. It can be seen in both scenarios that as carbon emissions decrease renewable technologies are selected. Wind turbine is selected

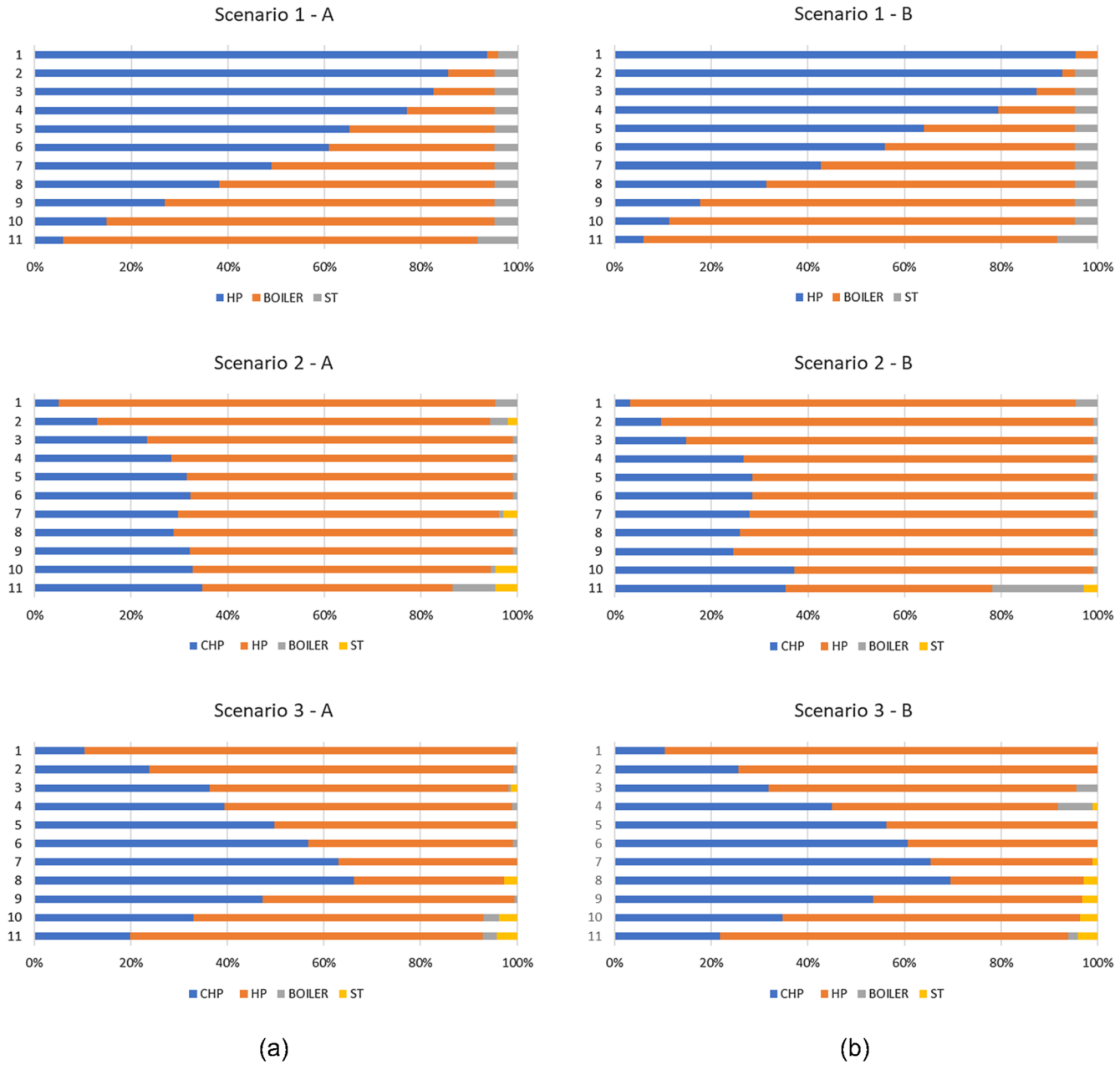


Fig. 13. Heating supply mix for Scenarios 1, 2 and 3, for: (a) “Method A” and (b) “Method B”.

in every solution in both scenarios and both methods. CHP units are installed in each solution for both methods. Absorption chillers are not installed in any solution in Scenario 2, where heat pumps satisfy both cooling and/or heating. In Scenario 3 absorption chillers are selected in every solution for both methods, except the first one (minimizing TAC). Regarding the design of DHN there are network links in every solution, for both methods. However, in “Method B” there are more links compared to “Method A”. The installation of pipes for the design of a DHN depends on the availability of generated heat to supply to the network. The fact that there are more connections in “Method B” compared to “Method A” implies that the available technologies supplying heat are oversized, which leads to overgeneration and higher cost.

Also, it is obvious that as solutions move towards the carbon emissions objective the capacity of less carbon intensive technologies, such as photovoltaics and solar thermal is increased. Moreover, it can be seen that storage technologies in Scenario 3 are selected. Specifically, thermal storage technology is selected in most solutions, whereas electricity storage is selected only in the last solution (carbon emissions objective) for both methods. This happens due to the higher cost of electricity storage and due to the ability of selling excess electricity to the grid which generates income. Finally, it is noted that microgrid is selected in all solutions in both methods, except for the first solution in “Method A” (minimizing cost). Besides that, microgrid offers the ability for buildings to exchange electricity which leads to less energy bought from the grid and therefore less emissions.

In Figs. 12–14 the supply mix of electricity, heating and cooling energy for Scenarios 1 to 3, for “Method A” and “Method B” are presented for the whole district. Regarding electricity mix, results follow a similar structure for both methods. It can be seen that in Scenario 2 and 3, as carbon emissions decrease the electricity supply from the grid is reduced and local electricity generation from CHP and renewables increases. In Scenario 3 electricity exchange through the microgrid also increases. Also, it is noted that a large share of electricity from renewables is sold to the grid, taking advantage of the high selling prices.

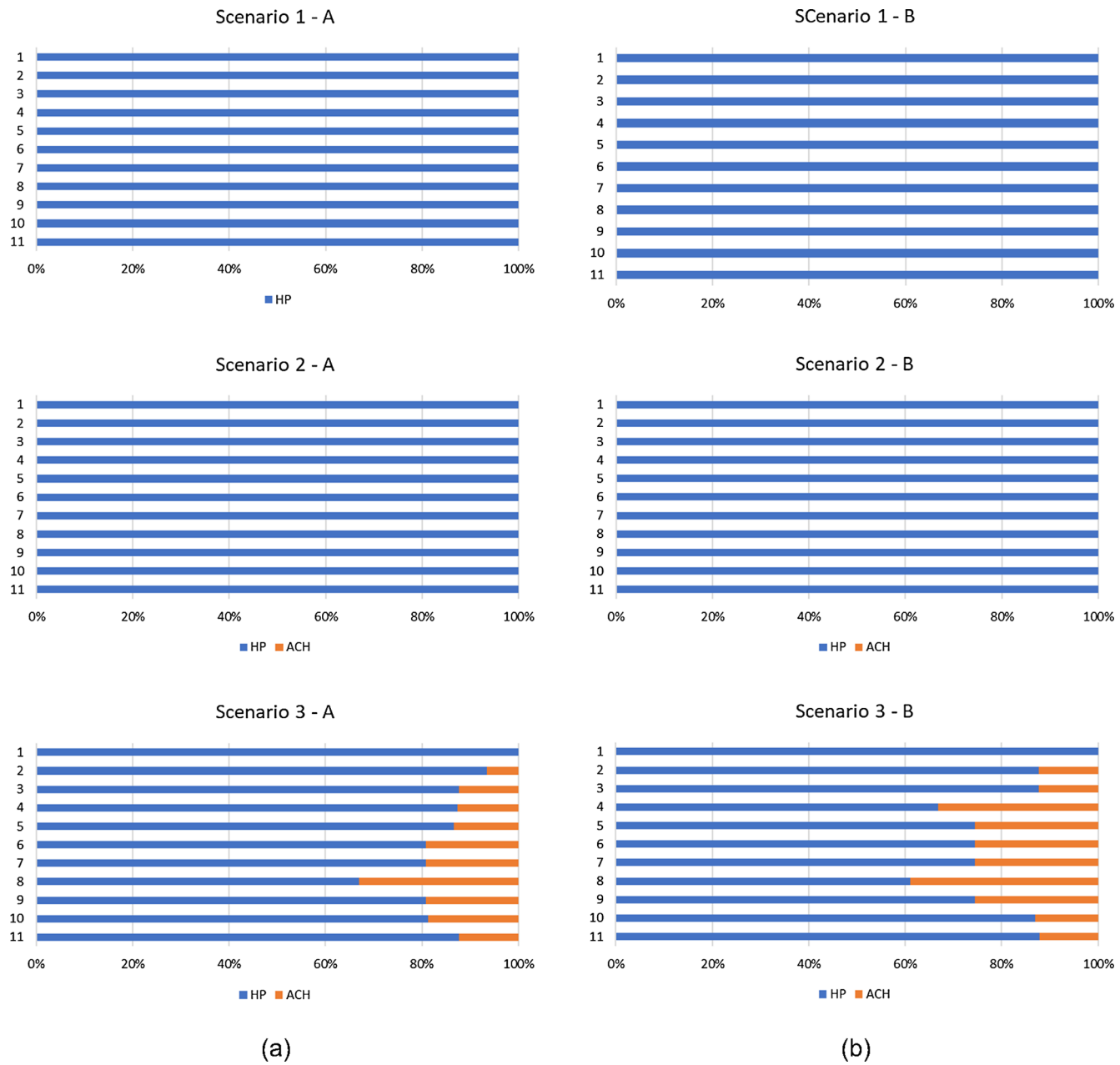
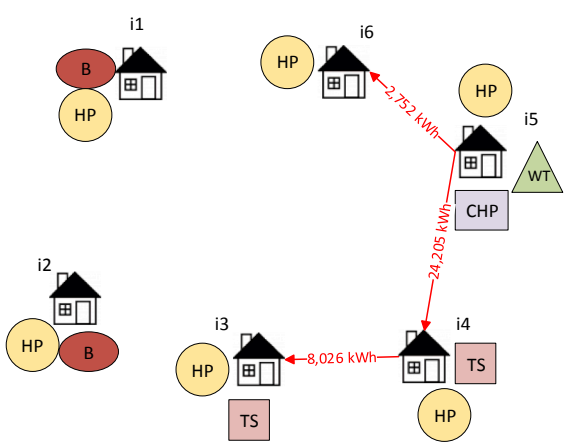


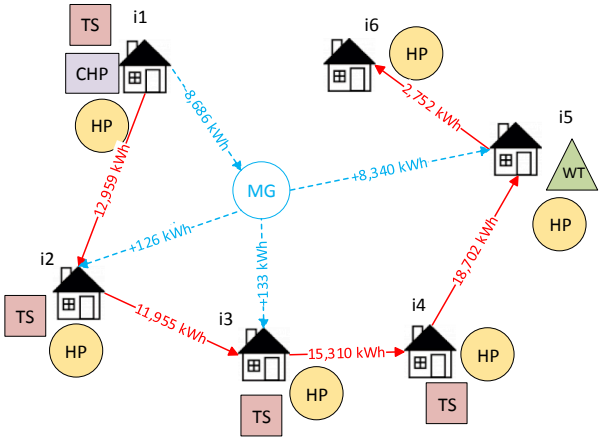
Fig. 14. Cooling supply mix for Scenarios 1, 2 and 3, for: (a) “Method A” and (b) “Method B”.

Mostly electricity is sold from wind turbines, followed by photovoltaics whereas electricity from CHP is used mainly for satisfying local demand. As for heat generation, in Scenario 1 the largest share of heat comes from heat pumps when the cost objective is dominant and as carbon emissions decrease natural gas boilers take over due to their low carbon emissions factor. Solar thermal technologies are also used to produce heat, except the first solution of “Method B”. On the other hand, in Scenarios 2 and 3 CHP is also used to produce heat in both methods. However, in those scenarios as carbon emissions decrease heat pumps are used more instead of boilers due to the use of “cleaner” electricity produced locally from renewables and/or CHP units. Finally, regarding cooling generation, in Scenario 1 only heat pumps (a/c units) are used. This is also the case for Scenario 2 where absorption chillers are not selected in any solution in both methods. In Scenario 3 absorption chillers are selected in all solutions except the one where TAC is minimized, however heat pumps are again the dominant technology.

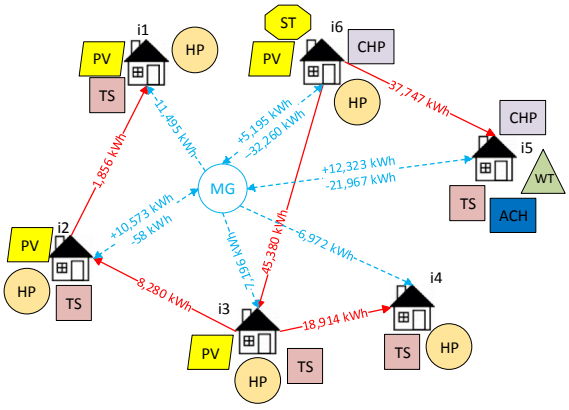
Although it can be seen in Figs. 12–14 that many solutions follow a similar structure in both methods, the differences between “Method A” and “Method B” are obvious. “Method A” can provide better solutions both in terms of TAC and carbon emissions due to the higher degrees of freedom. The direction of the optimization is not influenced and therefore a larger set of design solutions could be obtained [19]. However, although “Method A” offers the advantage of generating a larger set of solutions, the sizes of technologies that are selected might not be realistic and hence unavailable commercially. It can be argued that some technologies (e.g. CHP) could be custom made, therefore using “Method A” would provide the best optimal solution. However, this does not apply to all technologies. On the other hand, “Method B” uses commercially available technologies with predefined capacity. Nevertheless, in the context of designing a DES the complexity of selecting available technologies with specific size increases as the number of buildings increases. The task becomes even more complex if the formation of a microgrid or DHN or the use of storage technologies is an option. Choosing a technology configuration for a single building DES is



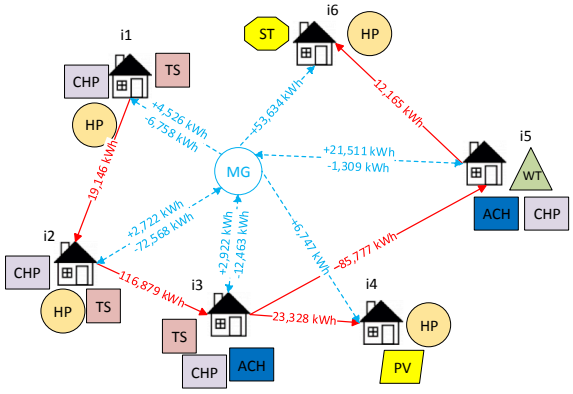
Method A – Point A



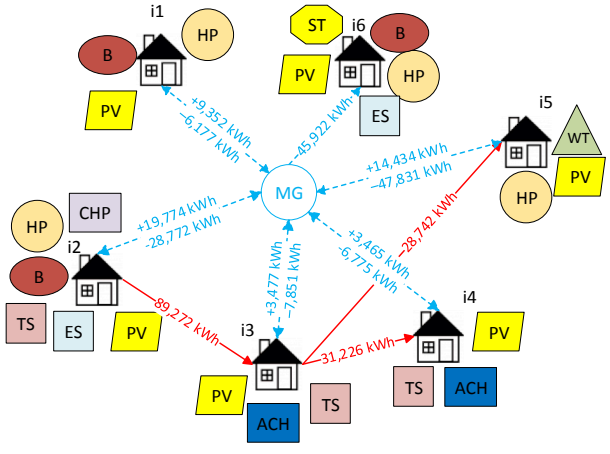
Method B – Point A



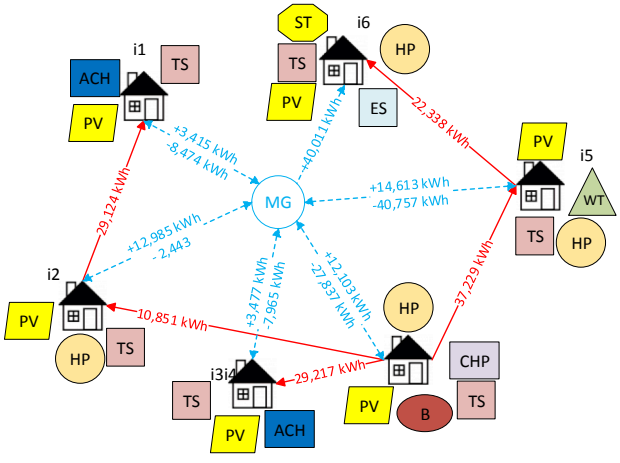
Method A – Point B



Method B – Point B



Method A – Point C



Method B – Point C

Fig. 15. Layout of DES for solutions “A”, “B” and “C” of “Method A” and “Method B” respectively, with heat flow through DHN and electricity exchange through microgrid throughout a year.

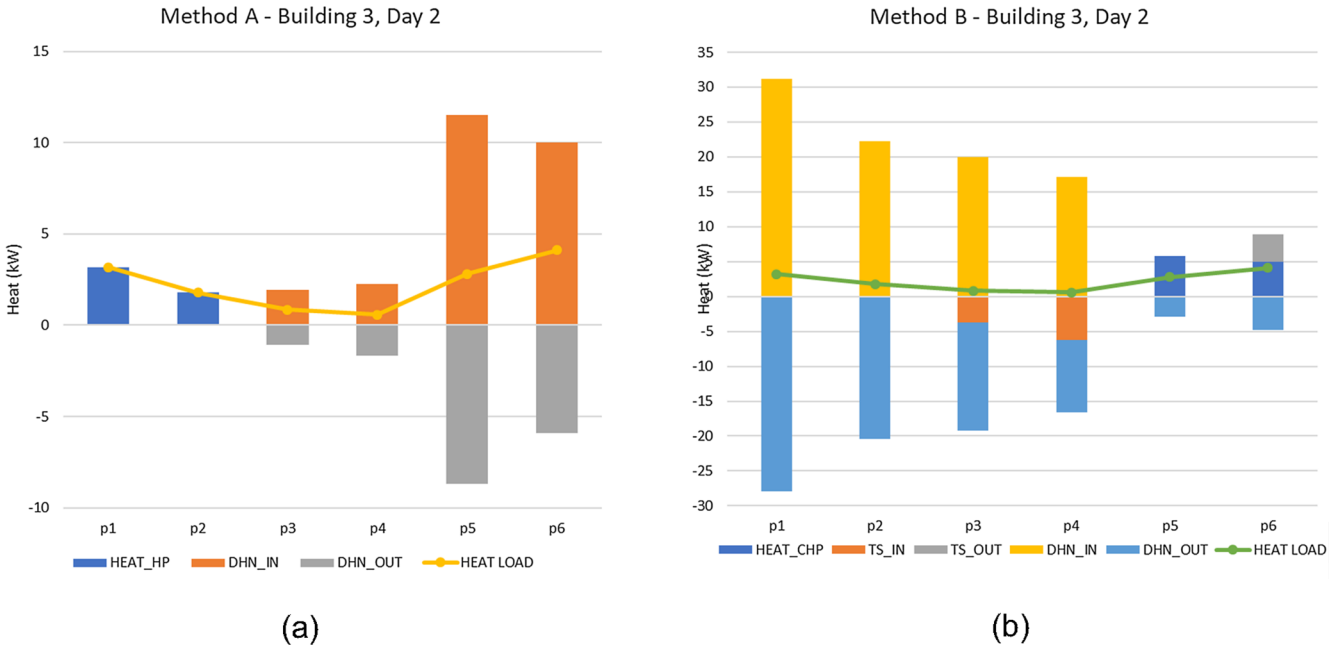


Fig. 16. Heat balance for building 3, scenario 3 for "Method A" and "Method B" (solution "B").

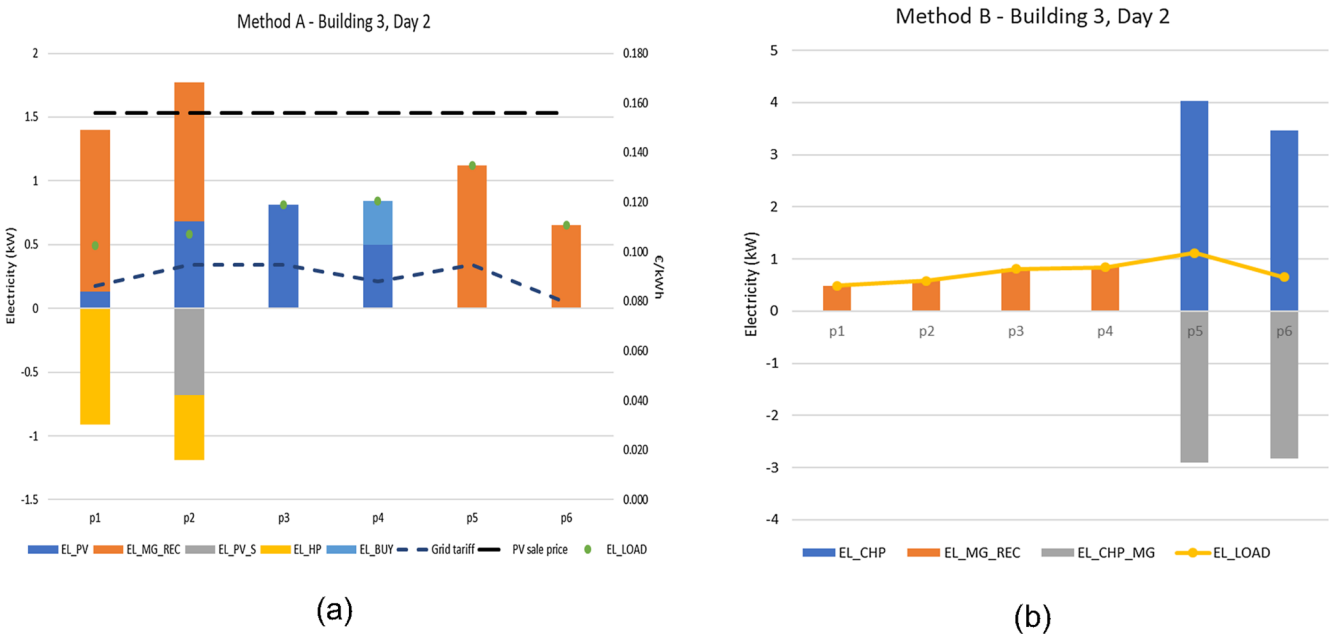


Fig. 17. Electricity balance for building 3, scenario 3 for "Method A" and "Method B" (solution "B").

a much easier task compared to the design of a DES for a whole neighbourhood or district.

In Fig. 15 an illustrative example of the system configuration is depicted for points "A", "B" and "C" shown in Fig. 8 for Scenario 3 of "Method A" and "Method B". Points "A", "B", and "C" represent the solutions for the case of the minimization of TAC, a "middle" solution and for the case of minimization of carbon emissions, respectively. It is obvious that points "A", "B" and "C" of "Method A" provide very different solutions compared to the respective points of method "B". Different technologies are installed at different buildings and a different DHN is installed at each solution. For instance, for the solution of Point "B" we can see the differences of system's configuration for both methods. In "Method A" a CHP is installed at buildings 5 and 6 while on the other hand in "Method B" a CHP is installed at buildings 1, 2, 3 and 5. Cooling is provided by heat pumps for all buildings, except building 5 in "Method A", and buildings 3 and 5 in "Method B" respectively, where absorption chillers are installed. Photovoltaics are installed at buildings 1, 2, 3 and 6 in "Method A", whereas only at building 4 in "Method B". Thermal storage is installed at buildings 1–5 in "Method A" and at buildings 1–3 in "Method B". Electrical storage is not installed at any building. A wind turbine is installed at building 5 in both methods. Also, the structure of the DHN is different. In "Method A" heat is supplied from building 2 to building 1, from building 3 to buildings 2 and 4, and from building 6 to building 3 and 5. On the other hand, in "Method B" heat is supplied from building 1 to 2, from building 2 to building 3, from building 3 to building 4 and 5, and from building 5 to building 6. Moreover, the electricity exchange through microgrid follows a different structure in the two methods. In "Method A" buildings

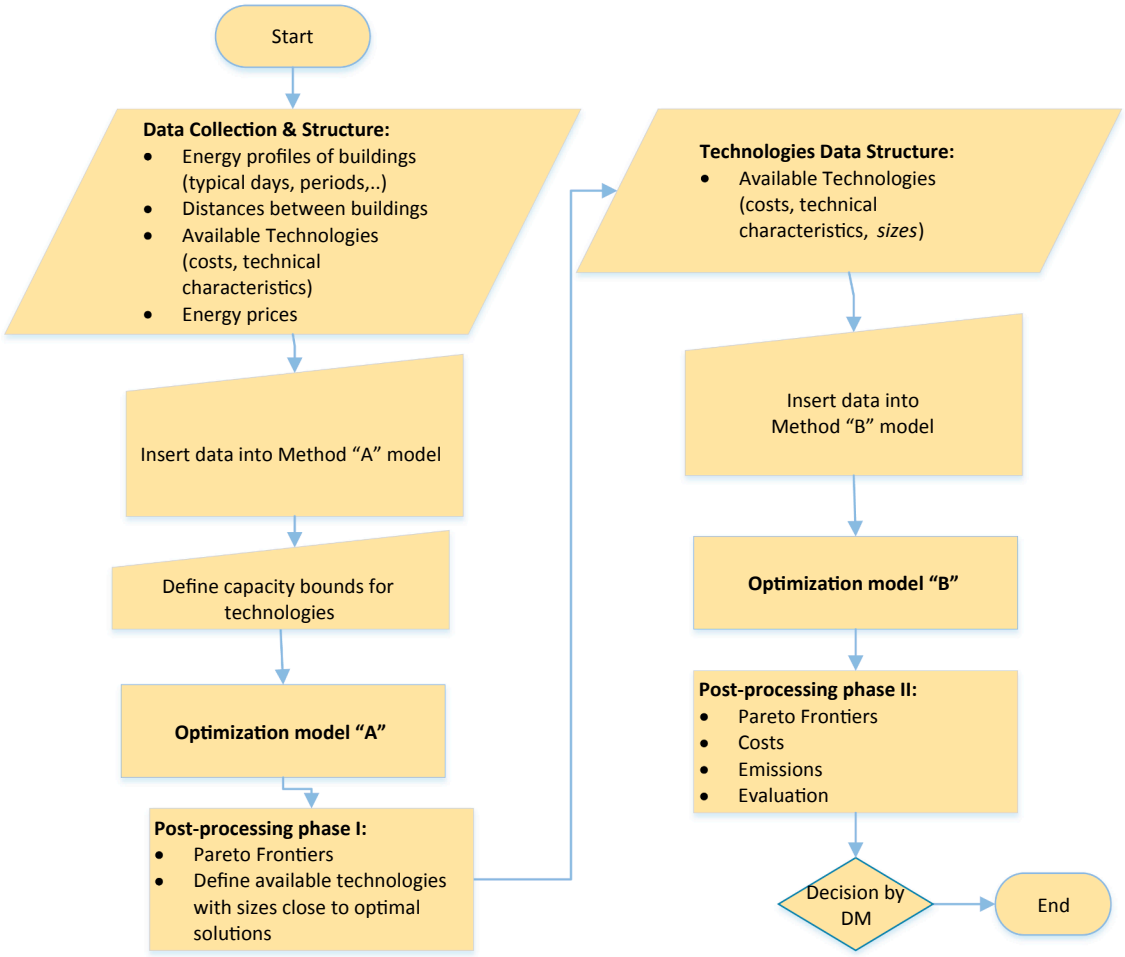


Fig. 18. Illustration of the possible combination of "Method A" and "Method B"

2 and 6 supply and receive electricity from the microgrid, whereas buildings 1, 3 and 4 only receive electricity from microgrid. On the other hand, in "Method B" buildings 1, 2, 3 and 5 supply and receive electricity from the microgrid, whereas buildings 4 and 6 only receive electricity.

The heat and electricity balances at building 3 of solution "B" for "Method A" and "Method B" for a typical mid-season day (day 2) are depicted in Figs. 16 and 17, respectively as illustrative examples. In "Method A" heat is produced by a heat pump unit in periods 1 and 2, where for the remaining periods, period 3 – period 6, heat demand is satisfied from heat transferred via the DHN. Also, a large portion of the received heat is exported through the DHN to satisfy the demand of other buildings. In "Method B" heat demand in periods 1–4 is satisfied only through the DHN. A thermal storage unit is also used to store energy at periods 3–5 and discharging it at period 6. Moreover, the installed CHP unit operates at periods 5–6 to satisfy the load and export heat to the DHN. Regarding the electricity balance, in "Method A" at periods 1–2, demand is satisfied mainly by energy received through the microgrid. Also, photovoltaics generate electricity at periods 1–4. However, at period 2 all the generated electricity from photovoltaics is sold to the grid taking advantage of the high energy price, while at period 3 the energy load of the building is covered only by photovoltaics. In period 4 a large portion of the electricity demand is satisfied by photovoltaics, but also energy is bought from the grid. In period 4 the purchase price of electricity is higher compared to period 3. Prices of buying and selling electricity can affect results significantly as they affect the operational cost, which contributes to the total annual costs. At periods 5–6 electricity demand is satisfied only through electricity received through microgrid. On the other hand, in "Method B" at periods 1–4 electricity demand is covered by electricity received from the microgrid. At periods 5 and 6 CHP covers the demand, and exports excess electricity to the microgrid.

The results show that solutions are sensitive, and the selection of the design method plays a significant role in the final configuration of a DES. While each solution might be optimal a decision maker has to choose amongst many available options with each one of them having different TAC and carbon footprint. Therefore, we suggest that these two methods could be used in parallel, as shown in the diagram depicted in Fig. 18. A decision maker could use "Method A" at first to get a picture of what the optimal configuration of the DES would be, then use "Method B" where technologies have sizes close to those provided by "Method A". The correct definition of sizes or bounds of the available technologies is very important, especially in a DES where the number of buildings is large, and when multi-objective optimization techniques are used for long-term energy planning. Moreover, the differences in TAC between the two methods, which are significant (as shown in Fig. 10) are a very important factor regarding the design and application of DES. The viability of a project is mostly evaluated by its financial results; therefore, a high TAC could make a DES project seem unattractive. The combination of the two methods could be proved useful regarding real applications, such as the design of a DES for an apartment complex, or a hotel which are long-term investments and the

results of capital and operational costs could affect the financial results of the project. Also, both methodologies are generic and could easily be modified to be used in any application.

5. Conclusions

In this article a multi-objective MILP optimization framework for the design of a distributed energy system is developed, using the minimization of TAC and of carbon emissions as objective functions. Distributed energy systems can take advantage of the locally produced energy and satisfy energy demand of a district in electricity, heating and cooling. Two methodologies, namely "Method A" and "Method B" have been developed with the first one performing a simultaneous sizing of available technologies, and the latter selecting technologies with a specific size from available sets. The scope of this article was to provide a comparison between those two methodologies. Both methods are generic and could be modified to be applied in different districts and use technologies of different sizes or bounds. Furthermore, three scenarios where depicted to examine the benefits of DES compared to the conventional design of energy systems.

The results show that Scenario 3 (DES) offers the best solutions, both in terms of cost and carbon emissions, compared to the other two scenarios, in both methods. In scenario 3 of "Method A" the best solution for total annual cost provides an 11% reduction compared to scenario 2, while in "Method B" a 4% reduction. Scenario 3 can reduce carbon emissions up to 81%, compared to scenario 2 in each method. It was shown that the integration of renewables, CHP units, storage technologies, the availability to form a microgrid for electricity exchange and the installation of DHN lead to the reduction of carbon emissions and to an increase of the total annual cost. Overall, DES could be used to satisfy local energy needs and reducing emissions which is very important towards tackling climate change.

Also, regarding the comparison between two methods, "Method A" is the one that offers the best solutions due to the flexibility it incorporates. Results showed that regarding total annual cost "Method A" offers solutions between 1% and 90% lower compared to "Method B" in Scenario 3. In terms of carbon emissions for scenario 3, "Method A" provides lower solutions, but the difference compared to "Method B" is about some 2%. However, solutions given with this method might not be available commercially, in which case "Method B" could be applied to provide more accurate results. The comparison of the two methods shows that solutions between the two methods are different regarding the values of objective functions. "Method A" has significantly lower values compared to "Method B". Moreover, the results show that each optimal solution in both methods has a different system configuration and operational profile of the technologies. The parallel use of the two methods is suggested as an alternative design methodology.

For future research, the design of DES under uncertainty will be examined in order to provide more robust results for such long-term planning problem.

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